

AD-A068 547

ALABAMA UNIV IN HUNTSVILLE SCHOOL OF SCIENCE AND ENG--ETC F/6 20/5  
INVESTIGATION OF TRANSIENT FLOW AND HEATING PROBLEMS CHARACTERI--ETC(U)  
MAR 79 C C SHIH, G R KARR, J F PERKINS DAAK40-77-C-0161

UNCLASSIFIED

UAH-RR-219

DRCPM-HEL-CR-79-8

NL

1 OF 4  
AD  
A068547



UAH Research Report No. 219

LEVEL

(2)  
nw

Technical Report TR-DRCPM-F-HEL-CR-79-8

AD A068547

INVESTIGATION OF TRANSIENT FLOW AND HEATING PROBLEMS CHARACTERISTIC  
OF HIGH ENERGY LASER GAS CIRCULATION SYSTEMS

Cornelius C. Shih  
Gerald R. Karr  
James F. Perkins

The University of Alabama in Huntsville  
School of Science and Engineering  
P. O. Box 1247  
Huntsville, AL 35807



March 1979

Final Technical Report: Contract DAAK40-77-C-0161

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

Period Covered: August 8, 1977 - March 31, 1979

Prepared for

High Energy Laser Systems Project Office  
U. S. Army Missile Research and Development Command  
Redstone Arsenal, AL 35809

Army High Energy Laser Laboratory  
U. S. Army Missile Research and Development Command  
Redstone Arsenal, AL 35809

DDC FILE COPY

79 05 11 025



#### **DISPOSITION INSTRUCTIONS**

**DESTROY THIS REPORT WHEN IT IS NO LONGER NEEDED. DO NOT  
RETURN IT TO THE ORIGINATOR.**

#### **DISCLAIMER**

**THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN  
OFFICIAL DEPARTMENT OF THE ARMY POSITION UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.**

#### **TRADE NAMES**

**USE OF TRADE NAMES OR MANUFACTURERS IN THIS REPORT DOES  
NOT CONSTITUTE AN OFFICIAL INDORSEMENT OR APPROVAL OF  
THE USE OF SUCH COMMERCIAL HARDWARE OR SOFTWARE.**

## **DISCLAIMER NOTICE**

**THIS DOCUMENT IS BEST QUALITY  
PRACTICABLE. THE COPY FURNISHED  
TO DDC CONTAINED A SIGNIFICANT  
NUMBER OF PAGES WHICH DO NOT  
REPRODUCE LEGIBLY.**

Final Technical Rept. 8 Aug 77-31 Mar 79

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report CR-79-8	2. GOVT ACCESSION NO. DRCPM-4-HEL	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Investigation of Transient Flow and Heating Problems Characteristic of High Energy Laser Gas Circulation Systems		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report August 8, 1977 - March 31, 1979
7. AUTHOR(s) Cornelius C. Shih Gerald R. Karr James F. Perkins		6. PERFORMING ORG. REPORT NUMBER UAH Research Report No. 219
9. PERFORMING ORGANIZATION NAME AND ADDRESS The University of Alabama in Huntsville School of Science and Engineering P. O. Box 1247, Huntsville, AL 35807		8. CONTRACT OR GRANT NUMBER(s) DAAK40-77-C-0161 new
11. CONTROLLING OFFICE NAME AND ADDRESS Headquarters U. S. Army Missile Command ATTN: DRSMI-IPBE/Florence, Redstone Arsenal, AL		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA 1X263314D093 AMCSC 623314.0930012
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 123456789		12. REPORT DATE March 1979
		13. NUMBER OF PAGES 306
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED 14 UAH-RR-219		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES 79 05 11 025		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) laser circulator, fluid and thermal characteristics of recirculating flows, acoustic attenuators, numerical analysis of the recirculating flow.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Complementing the Army effort on the Closed Cycle Circulator for repetitively pulsed electric discharge lasers, a project was conducted to develop computer programs modeling the recirculating gas flows in pulsed laser operation including steady and unsteady cases; to perform theoretical analysis of the unstable resonator with tilted spherical mirrors; to conduct an experimental investigation of transient fluid and thermal characteristics of the recirculating flow associated with the pulsed laser operation using		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE  
S/N 0102-014-6601

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)



20. (continued)

a subscale circulator; and to experimentally determine the effects of mufflers, screen packs, and honeycombs on acoustic and thermal waves propagated in the recirculating flow.

ACCESSION for	
NTIS	White Section <input checked="" type="checkbox"/>
CDC	Blue Section <input type="checkbox"/>
UNANNOUNCED	<input type="checkbox"/>
JUSTIFIED	
BY	
DISTRICT/COMMUNITY CODES	
SPECIAL	
A L	

## TABLE OF CONTENTS

Chapter		Page
I	INTRODUCTION	1
II	EXPERIMENTAL ANALYSIS OF SUBSCALE CLOSED CYCLE LASER GAS CIRCULATOR	3
	A. Experimental Apparatus Description	3
	1. Recirculating Flow System	3
	a. Blower Specifications	3
	b. PVC Piping	5
	c. Dimensions	5
	d. Flanges	5
	e. E-Beam Mask	5
	f. Cavity Structure	7
	2. Mufflers	7
	3. Screen Packs	16
	4. Instrumentation Systems	17
	a. Pressure Measurement	17
	b. Temperature Measurement	18
	c. Velocity Measurement	18
	B. Presentation of Experimental Data	19
	C. Discussion and Analysis of the Data	20
III	NUMERICAL ANALYSIS OF TRANSIENT FLOW PROBLEMS RE- SULTING FROM PULSED ENERGY INPUT	21
IV	NUMERICAL ANALYSIS OF STEADY FLOWS IN THE CLOSED CYCLE CIRCULATOR	26
V	ANALYSIS OF OPTICAL RESONATORS WITH TILTED SPHERICAL MIRRORS	59
VI	CONTRIBUTIONS TO TECHNICAL CONFERENCES	74

APPENDIX A	130
APPENDIX B	131
APPENDIX C	230
APPENDIX D	246
APPENDIX E	291
DISTRIBUTION LIST	299



## Chapter I

### INTRODUCTION

Operation of a high energy pulsed laser presents problems of acoustics and thermodynamics owing to the generation of shock waves and a heated gas slug which are a result of sudden energy deposition and wave interaction with other laser components. In addition, other transient problems of fluid dynamics and thermodynamics are involved during the start-up of a high energy laser gas circulator from a room temperature, zero flow initial condition until the establishment of steady flow conditions for a sustained repetitive pulsed operation. These start up transients are characteristic of all high energy gas laser systems, both pulsed and cw, and both open and closed cycle to varying degrees. The main purpose of this project is to investigate transient fluid and thermal characteristics of high energy pulsed laser operations and to develop methods of reducing or eliminating the acoustic and thermal problems detrimental to the laser beam quality. In this technical direction, a program was initiated at the Army Missile Command to design, fabricate and test a unique small scale closed cycle gas circulator for repetitively pulsed electric discharge lasers to establish a technology data base for understanding the laser operation. Technical issues relating to operating such a system will be identified and methods of solving these technical problems may be developed and tested. The circulator, with a 28,000 rpm compressor, operates at 200 - 300 °K and 0.8 - 1.2 atm pressure. Complementing this Army effort, the UAH project was planned: to develop computer programs modeling the recirculating gas flows in pulsed laser operation including steady and unsteady cases; to perform theoretical

analysis of the unstable resonator with tilted spherical mirrors; to conduct an experimental investigation of transient fluid and thermal characteristics of the recirculating flow associated with the pulsed laser operation using a subscale circulator; and to experimentally determine the effects of mufflers, screen packs and honeycombs on acoustic and thermal waves propagated in the recirculating flow.

Some of these efforts are improvements and modifications of the efforts noted in the previous year's report. Results of this project are useful as a technical guide for the development of the Army Closed Cycle Circulator as well as of direct interest to those concerned with all types of pulsed laser systems.

Contributions to this report were made by: G. R. Karr in Chapter IV; J. F. Perkins in Chapter V; David Walker in Chapter III; W. Dahm in Chapter II, under general technical direction of C. C. Shih.

## Chapter II

### EXPERIMENTAL ANALYSIS OF SUBSCALE CLOSED CYCLE LASER GAS CIRCULATOR

The closed cycle gas circulator used in this study was designed for use with the MICOM single pulse e-beam controlled CO<sub>2</sub> laser. It was originally developed to initiate an experimental investigation on the transient flow and heating problems characteristic of high average power pulsed laser operation in closed cycle systems. The effort reported herein is an extension of the work performed in the year 1976-77 that includes design improvements in the cavity section and two perforation type mufflers and two sizes of screen packs.

#### A. Experimental Apparatus Description

##### 1. Recirculating Flow System

The recirculation system consisted of a blower, poly vinyl chloride (PVC) piping, mounting flanges for attachment to the e-beam laser, an e-beam mask, and a plastic structure which was mounted inside the laser cavity. The laser was made by Systems Science and Software (S<sup>3</sup>). A schematic of the system attached to the S<sup>3</sup> laser is given in Figure 1. The flow through the cavity region is from right to left in that figure.

##### a. Blower Specifications

The blower is a Dayton Model 4C108 with a 10 5/8" wheel. The inlet is 6½" in diameter. The outlet is 2½" square. The outside of the blower casing is approximately 13" in diameter.

The motor is connected directly to the blower wheel. The motor is a 1 hp Dayton Model 6K232 operated at 3450 rpm.



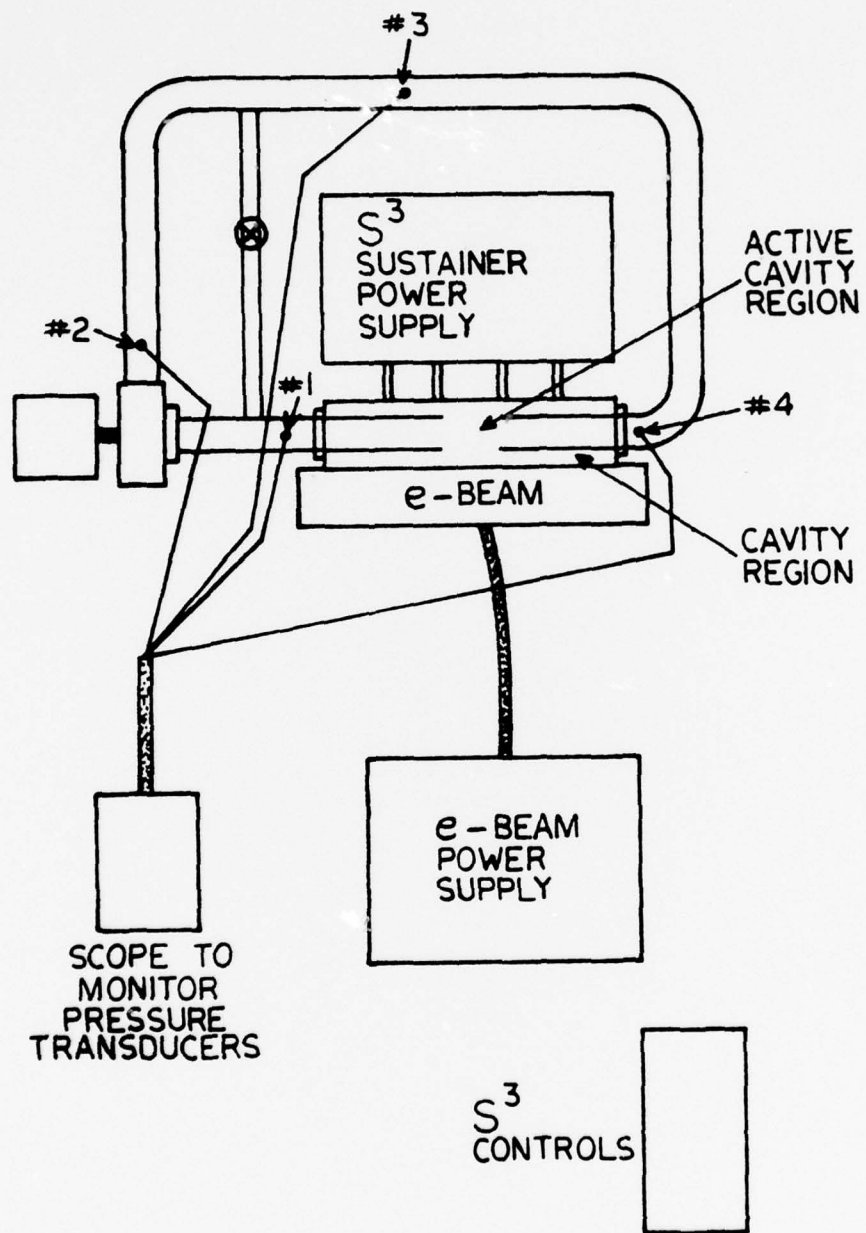


FIGURE 1. TOP VIEW OF PVC SUBSCALE MODEL ATTACHED TO THE  $S^3$  LASER.

b. PVC Piping

The majority of the piping consisted of 3109662 "Certain-Teed Plastics" 4" PVC 1120 Schedule 40 220 psi Astmd-2665. This pipe has 4" ID and 4½" OD. The 90° turns were achieved using standard PVC fittings which have a 4" radius of curvature along the center line of the 90° bend. A number of couplings were employed throughout the path length to accommodate assembly, disassembly, and modification during the testing.

Also shown in Figure 1 is a cross-over or by-pass pipe with valve. This pipe was J24G264 1" PVC 1120 Schedule 80 630 psi at 73°F ASTM D 1785. The pipe was 1" ID and 1½" OD and was attached to the 4" PVC through a standard 4" to 2" tee with a reducer used to bring the size down to 1". A 1" gate valve was used in the 1" line.

c. Dimensions

The piping dimensions are shown in Figure 2 in centimeters. Total path length around the 4" circuit is approximately 1140 cm (37 ft.).

d. Flanges

Special flanges had to be constructed in order to attach the PVC pipe to the blower and to the S<sup>3</sup> laser. For the blower attachment, a 6" to 4" reducer was used on the inlet side and an aluminum piece was machined to go from the square to the circular cross-section.

The flanges for attachment to the S<sup>3</sup> were constructed from aluminum consisting of 4½" diameter holes with suitable bolt circle and o-ring groove.

e. E-beam Mask

For this test series, an E-beam mask of 45 cm by 10 cm (height) was used with an improved method of base line gas flow and leak control using simple structural changes with taping and caulking with silicone glue.





#### f. Cavity Structure

The cavity structure serves to box in the discharge region in the vertical and longitudinal directions and also to provide a support for the PVC pipe. Since the wave distortions discovered in the previous tests were determined to be attributed to pressure leaks from the structure, a special caution was applied for sealing the cavity structure in contact with the sustainer electrode as well as the 45 cm E-beam mask. A sketch of the cavity structure is shown in Figure 3.

#### 2. Mufflers

A horn-coupled muffler and a cannister type muffler was designed, constructed and tested on the acoustic test bench and then in the circulator. Detailed dimensions of the mufflers are shown in Figures 4 and 5, respectively. On the acoustic test bench, each muffler was subjected to sound waves of fixed frequencies ranging from 100 HZ to 110 KHZ for determining its effectiveness as an acoustic attenuator. The test setup shown in Figure 6 provides the means of using the same acoustic source for pipe sections with and without the muffler of interest. This will prevent any nonuniformity in wave characteristics from two different sound sources even though the indicator shows that they are the same. This setup also allows for the monitoring of the input to the system since the input wave form is also put on the oscilloscope. Thus, any drift in the amplifiers can be corrected during the experiment. Results of acoustic bench tests for both horn-couples and cannister mufflers are presented in Figure 7. Both mufflers were found to perform well in the low frequency region with peak  $d_{\beta}$  difference of 20 to 30. The horn-coupled muffler shows a flatter response in the low frequency region than the

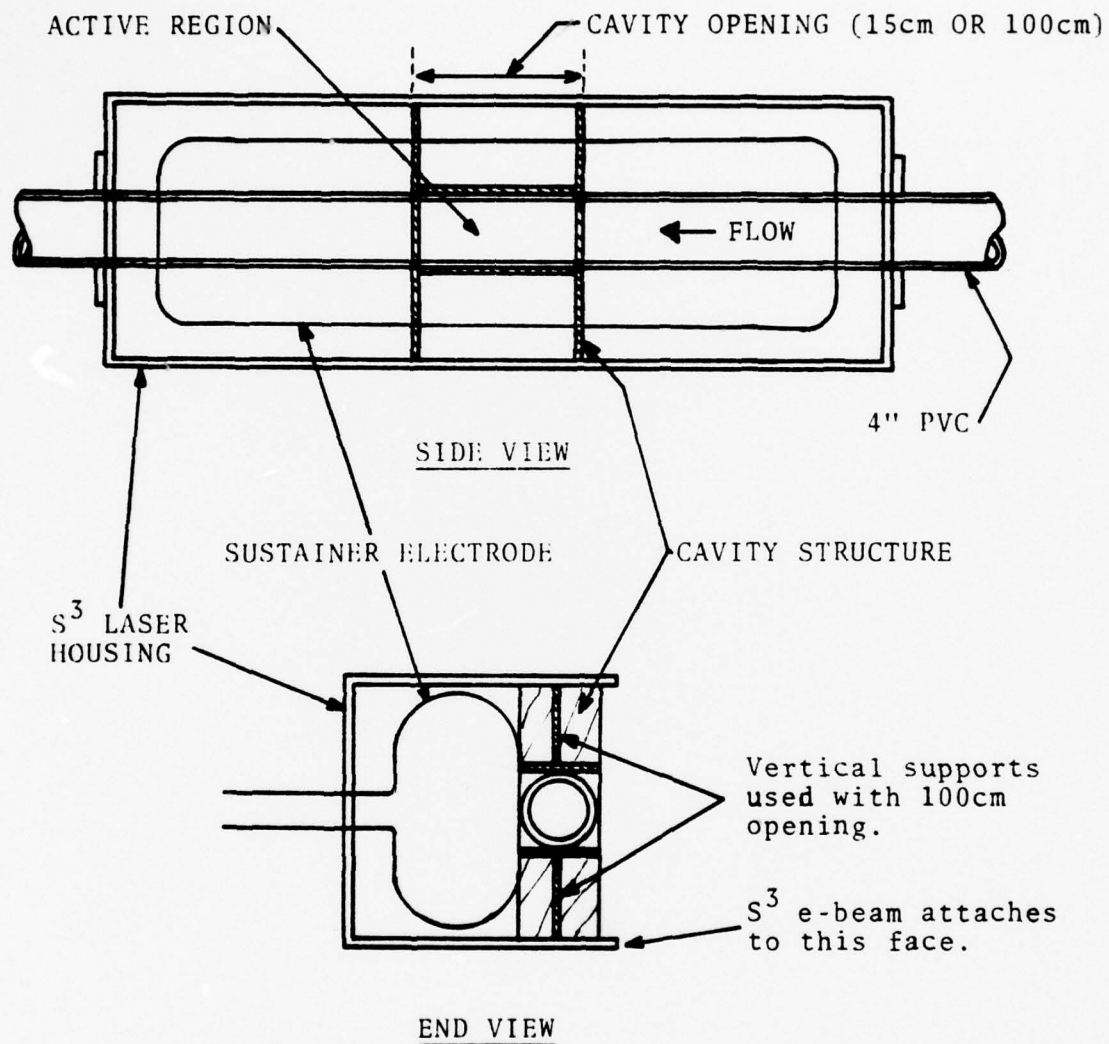


FIGURE 3. SKETCH OF CAVITY STRUCTURE AND INSTALLATION INSIDE THE  $S^3$  LASER HOUSING.

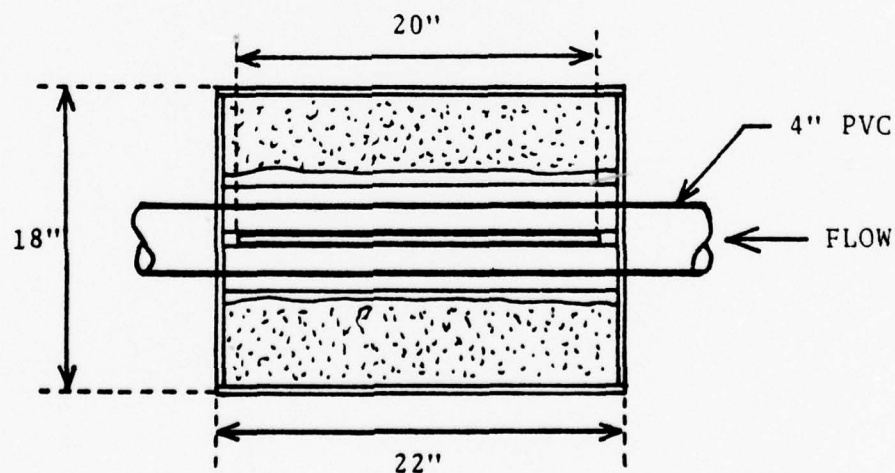
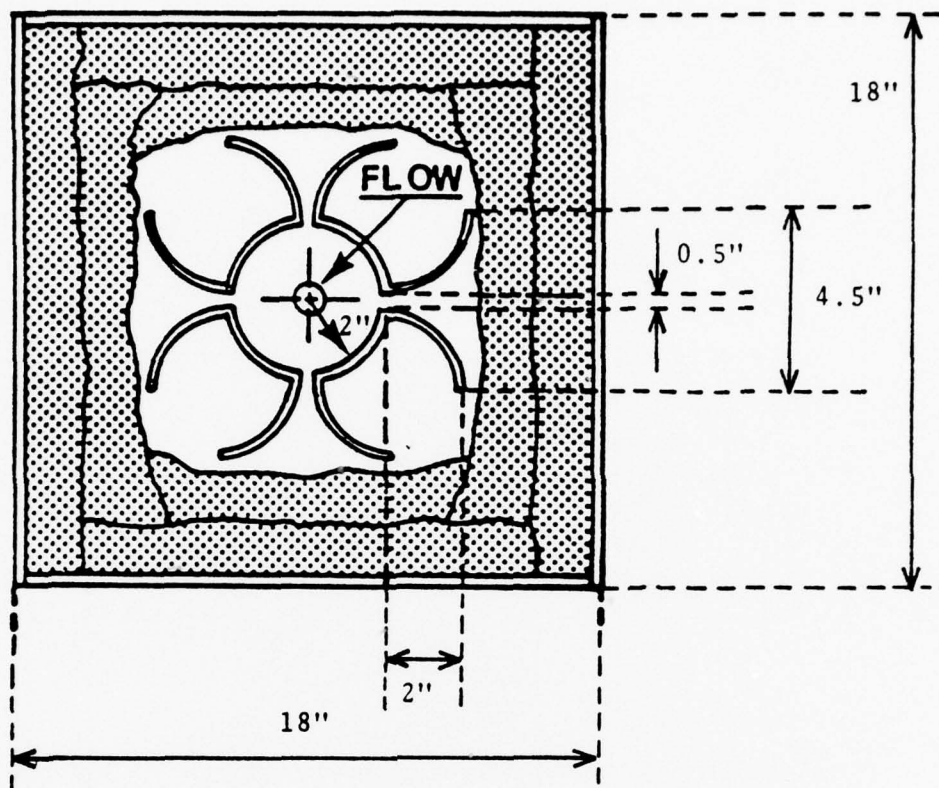


Figure 4. SKETCH OF MUFFLER.  
Curved pieces constructed of 4" PVC piping,  
sides of box constructed of  $\frac{1}{4}$ " plywood,  
and end pieces constructed of  $\frac{1}{2}$ " plexiglass.



FIGURE 5

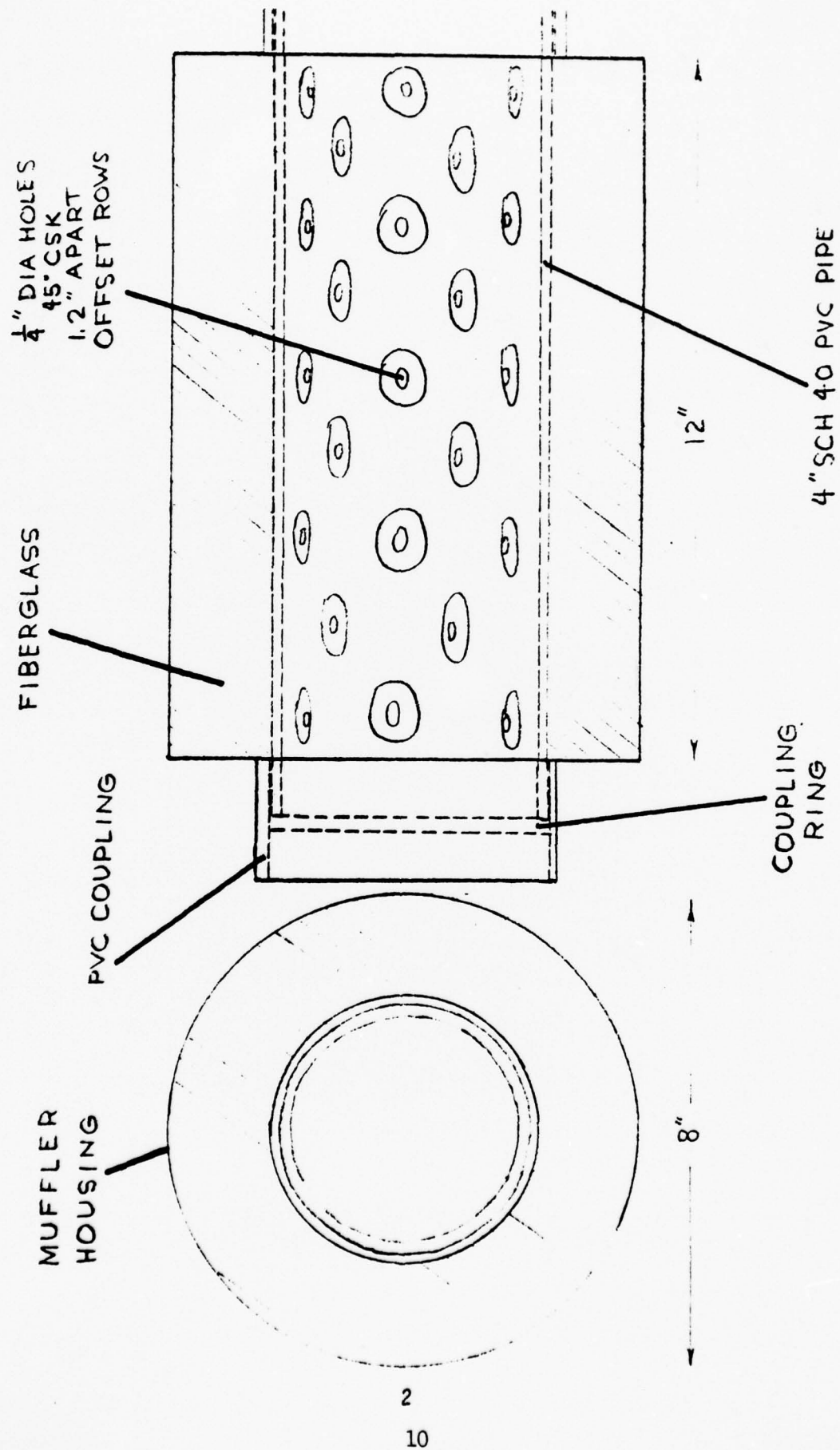


Figure 5. ACOUSTIC MUFFLER

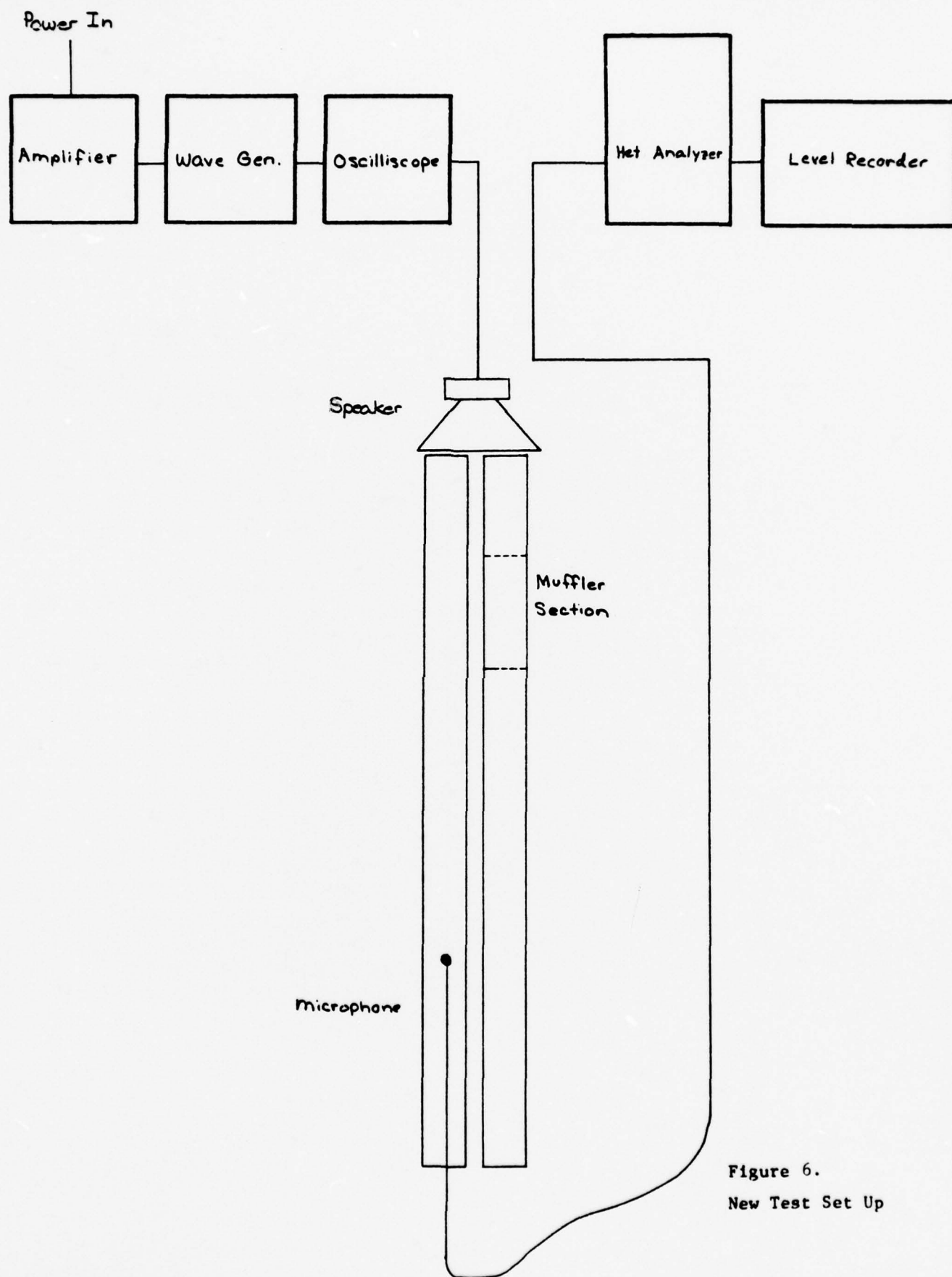
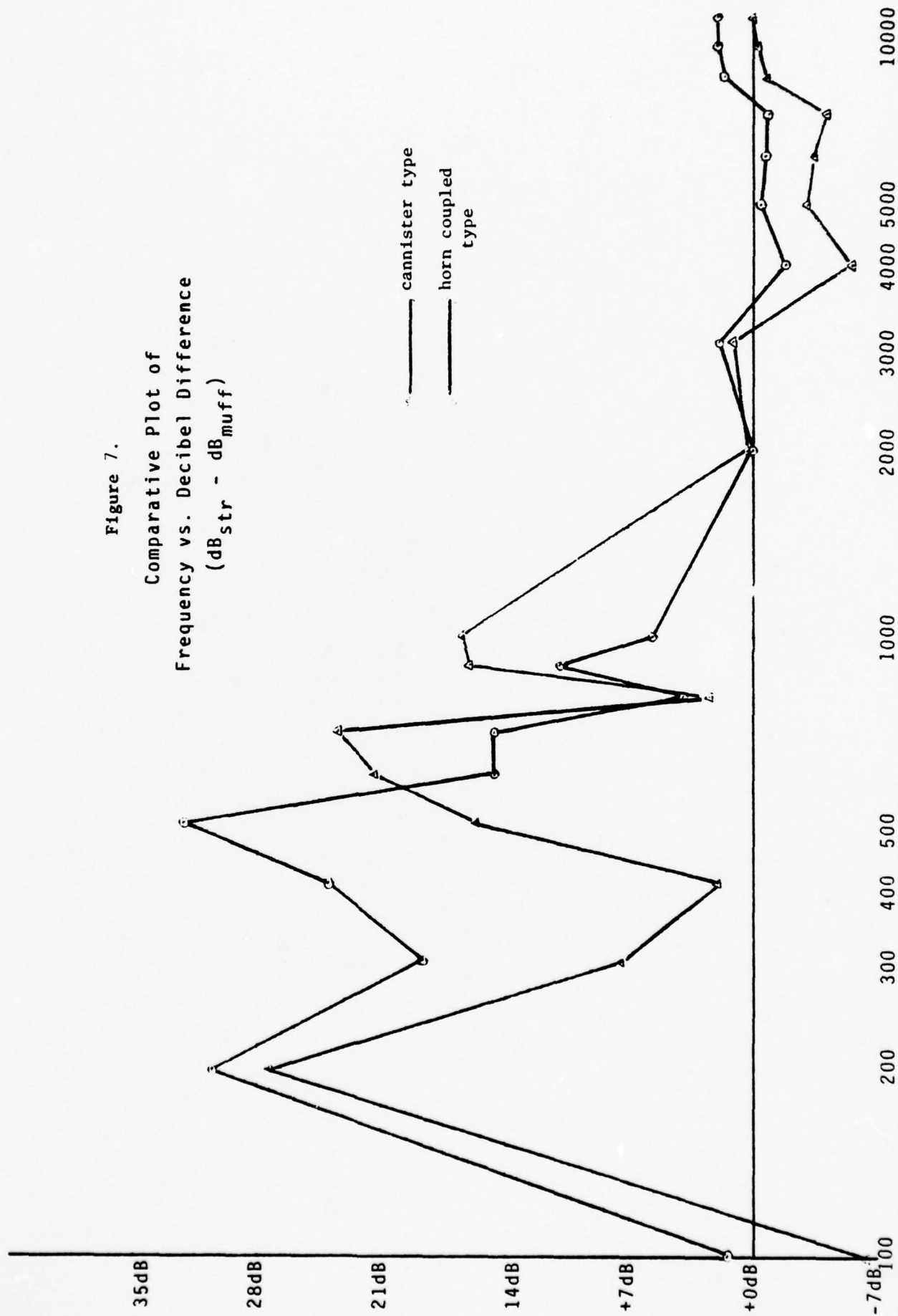


Figure 6.  
New Test Set Up

Figure 7.

Comparative Plot of  
Frequency vs. Decibel Difference  
( $\text{dB}_{\text{str}} - \text{dB}_{\text{muff}}$ )



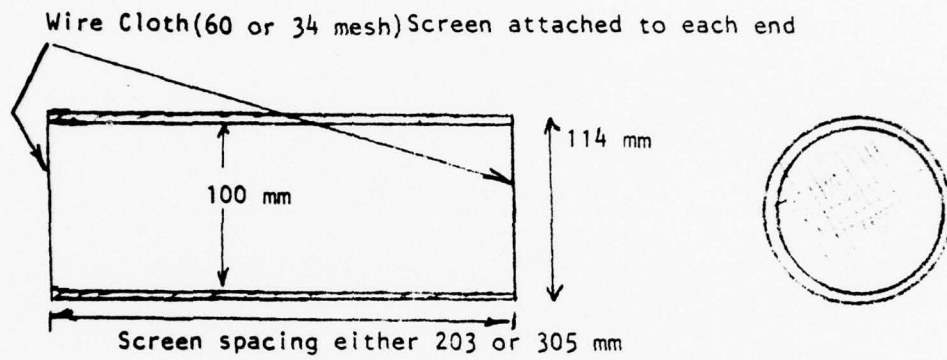
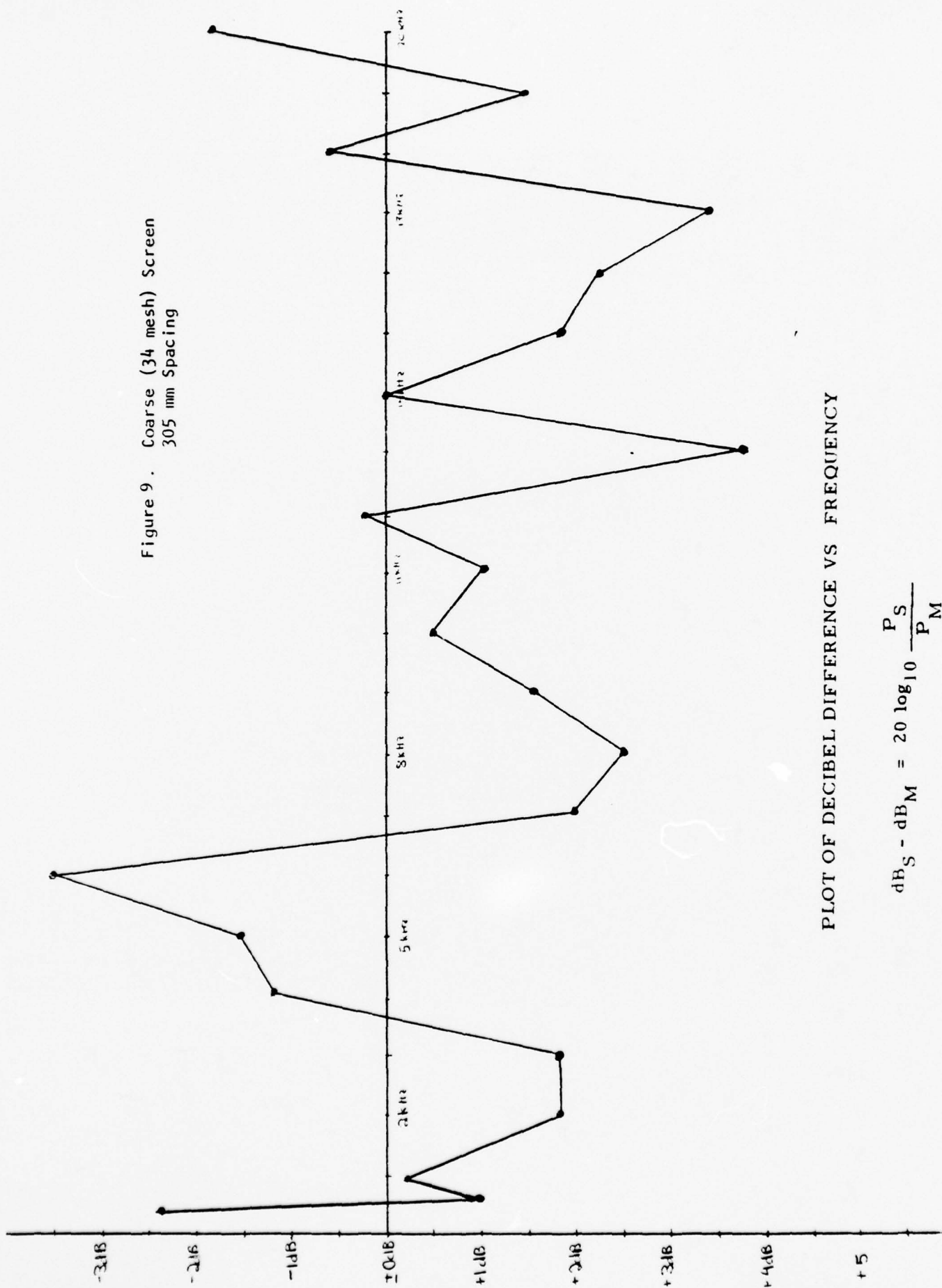


Figure 8. Screen Pack Test Section Design



Figure 9. Coarse (34 mesh) Screen  
305 mm Spacing



PLOT OF DECIBEL DIFFERENCE VS FREQUENCY

$$dB_S - dB_M = 20 \log_{10} \frac{P_S}{P_M}$$

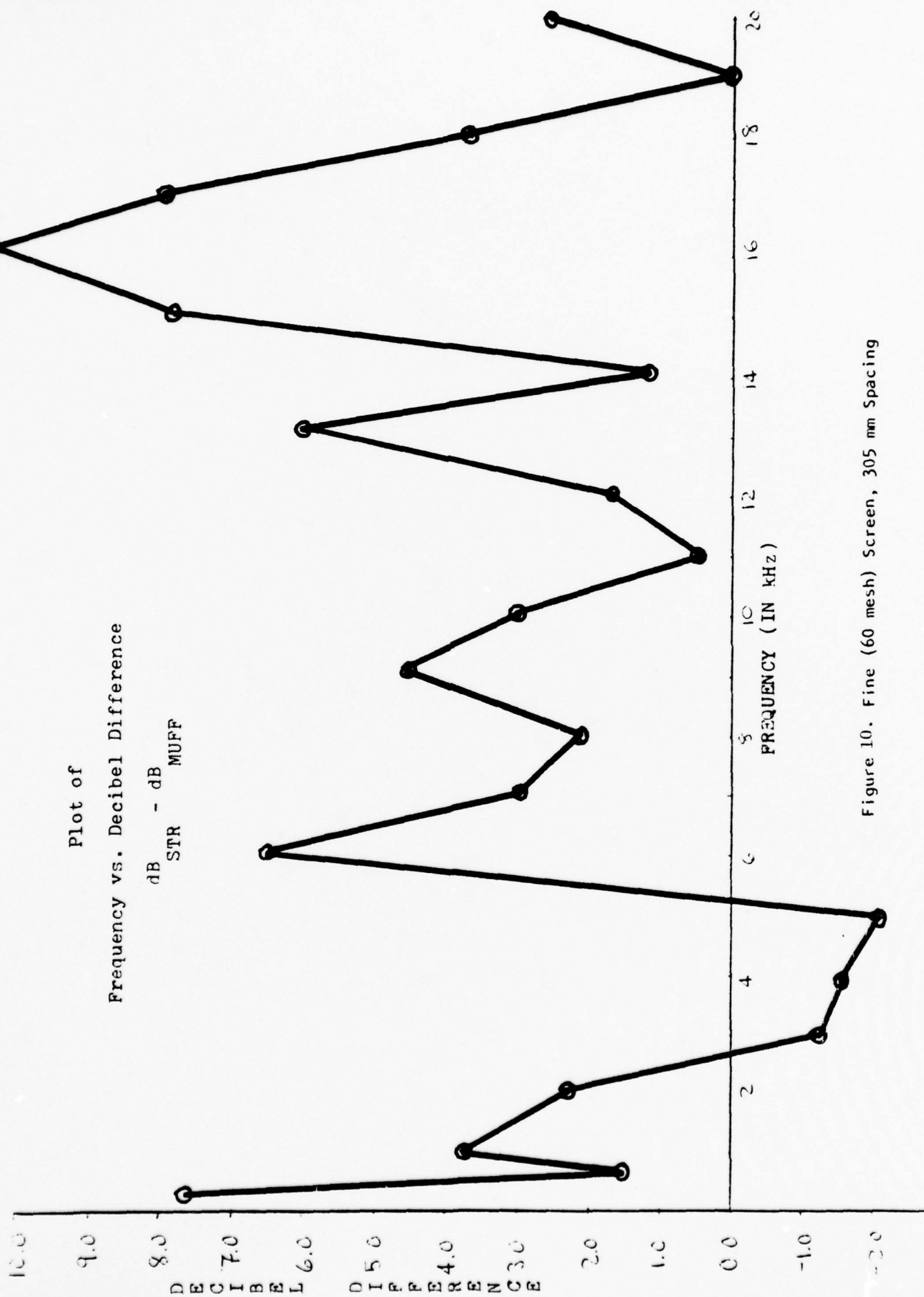


Figure 10. Fine (60 mesh) Screen, 305 mm Spacing

cannister type. The cannister muffler shows an effective damping at the 400 HZ point. Above 2000 HZ, neither muffler shows significant muffling characteristics. B & K test equipment was used on the acoustic test bench for the acoustic measurement.

### 3. Screen Packs

The use of screen packs has been accepted as one of the most common methods of conditioning or suppressing the level of turbulence in a confined fluid stream such as a wind tunnel test section. At the suggestion of Poseidon Research, two screen mesh sizes (60 mesh per inch with 0.004 in. wire size at 55% open area; 34 mesh per inch with 0.0065 in. wire size at 55% open area) shown in Figure 8 were tested on the acoustic test bench in the same fashion as the mufflers. The screen packs were constructed using two sheets of screen at two spacings, 203 mm and 305 mm. Thus, four test pieces were constructed and tested on the bench.

Both the fine (60 mesh) and coarse (34 mesh) screens were tested using the wide (305 mm) spacing. The results of testing over the frequency range from 1 to 20 KHz are presented in Figure 9 for the coarse (34 mesh) screens on 305 mm spacing and in Figure 10 for the fine (60 mesh) screens on the same spacing. Note that the vertical axis are reversed in sign in the two figures.

The results show that the fine (60 mesh) screen is generally more effective over the frequency range tested. Figure 10 shows a  $d_{\beta}$  difference between the straight pipe and the pipe with screens of about  $4 d_{\beta}$  on the average while Figure 9 shows only a  $2 d_{\beta}$  difference for the coarse (34 mesh) screens. Both screens show different peaks at 16 and 13 KHz with a general increase also in the 7 - 10 KHz region. Both screens also show a negative value in the 4 - 6 KHz range.

#### 4. Instrumentation System

##### a. Pressure Measurement

The instrument used for pressure measurements is a battery of four Piezotron pressure sensing units each of which consists of a piezoelectric pressure transducer (Type 201B5) and a coupler (549B) connected with a 128M cable. The unit is then connected to an oscilloscope for the readout of voltage signals. Specifications of the Piezotron miniature pressure sensor or transducer, the Piezotron coupler, and the Textronix oscilloscope are presented in Appendix A.

The pressure of up to 100 psi was sensed by the mini-gage which gives a direct, high level, voltage signal with less than 100 ohms output impedance and high frequency response of 50 KHz and low frequency response of 0.005 HZ. The sensor then converts the pressure into electrical voltage with bias of up to  $11 \pm 2$  volts. The power required by the transducer to operate is supplied by the coupler, and the signal from the transducer to the readout equipment is transmitted through the coupler over a single inexpensive cable. This eliminates all of the inherent piezoelectric high impedance problems of electrical leakage, cable noise and signal attenuation and allows the transducers to be used in contaminated environments and with long and moving cables at low noise and without use of charge amplifiers.

The calibration of the transducers was performed at the factory, and the values of the calibration were noted to be, on the average for all probes, 50 mv per psi for the pressure measurement up to 100 psi. The calibration curve relating the voltage output and the pressure is noted to be quite lenient.



#### b. Temperature Measurement

Due to the extremely transient nature of temperature variation in the recirculating flow as a result of the pulsed laser operation, a sensor of high frequency response in excess of 1 KHz is considered necessary for the temperature measurement. Search of an adequate sensor resulted in the selection of a hot-wire sensor made of 0.00015 in. diameter tungsten wire coated with platinum powdery film. The hot-wire sensor is connected to the Temperature and Switching Module (Thermo-Systems Model 1040) which is in turn connected to the power supply (Model 1031-10A).

The Module consists of a bridge circuit and amplifier in an open loop configuration so the hot-wire sensor which is ordinarily used as an anemometer probe can be switched to function as a resistance thermometer. Since there is a linear proportionality between the voltage output and the temperature, the calibration can be simply performed by adjusting the zero and gain set potentiometers to a desired temperature range using the calibrate pots of two temperatures.

#### c. Velocity Measurement

For the measurement of velocities, hot-wire probes the same as those used for the temperature measurement is applied. The probe is connected to the constant temperature anemometer module (Model 1010A). The amplified output signal from the anemometer is sent to the Linearizer (Model 1005B) so that the voltage signal is processed in such a way that it became linearly related to velocity of the gas flow.

The use of these modules ensures the frequency response above 500 KHz with power output as high as 1.5 amps. The noise associated with the anemometer is noted to be less than 0.007% equivalent turbulent intensity.

Frequency response to the Linearizer is found to be up to 400 KHz and the accuracy of linearization can reach  $\pm 0.2\%$ . With these special features of the instrument, it is able to measure both average velocity and turbulence in one-dimension.

Calibration of the probe is performed by using a Thermo-Systems Calibrator (Model 1125) in accordance with the furnished instructions. The readout system for both temperature and velocity is the Tektronix type oscilloscope (Type 564-3A74-3B3).

#### B. Presentation of Experimental Data

An experimental run typically involved firing the  $S^3$  laser and recording pressure, temperature, and/or velocity at various locations in the circulator. In addition, the laser discharge current was also monitored for each run in order to determine the power put into the gas flow. Data collected from each run were recorded with two Polaroid photos: one for laser energy deposition and one for fluid and thermal characteristics, along with readings from other indicators. Plates 5381 to 5523 presents the data and complete information regarding the test runs on one figure to a test run basis. These plates are presented in Appendix B.

The tests were designed to investigate the fluid-thermal disturbances produced by the sudden energy deposition in the cavity section of the circulator.

A list of all test runs, with appropriate details, made during this project period is attached as Appendix B.

Based on the previous experience, pure nitrogen gas was found adequate for approximating the laser gas characteristics in the experiment of interest. Thus, nitrogen was used in all test runs for the sake of convenience and economy.

### C. Discussion and Analysis of the Data

The  $S^3$  laser without lasing action merely provided the deposition of energy in the cavity section, thereby simulating the energy pulse generated in such a laser. The E-beam was operated at 90 KV, the sustainer voltage was varied between 15-30 KV, and the pulse width was varied between 2 and 3  $\mu$  sec.

As pertains to the fluid dynamics of the cavity flow, the energy deposition is considered instantaneous and, therefore, the process can be described as an instantaneous constant volume heating process. The gas pressure and temperature are instantaneously increased by the energy deposition while the density remains unchanged. As the flow transports the heated slug of high pressure gas away from the cavity, the frictional resistance and thermal diffusion will take place in the heated slug of gas, causing its deterioration of fluid and thermal characteristics.

Detailed discussion and analysis of the data of some typical test runs are presented in Chapter VI, Sections 2, 3, and 4.

### Chapter III

#### NUMERICAL ANALYSIS OF TRANSIENT FLOW PROBLEMS RESULTING FROM PULSED ENERGY INPUT

##### A. Theoretical Considerations

As an input of pulsed energy is made into the laser cavity, disturbances in the form of shock waves and thermal changes will travel out from the cavity, overriding the recirculating laser gas flow. These phenomena are modeled by a set of governing equations of fluid dynamics and thermodynamics with the one-dimensional assumption.

Details of the theoretical model including the governing equations, boundary and initial conditions, formulation of the method of characteristics, finite difference schemes and the flow diagram are delineated in the UAH Research Report No. 199 (March 1977), pages 7 through 24. For the sake of brevity, they are not repeated here, and their reference is made to the 1977 report. The computer program modified from the 1977 version is presented in Appendix C.

##### B. Presentation of Numerical Results

After several modifications and improvements of the computer program pertaining to the transient flow problems of interest, the program has been developed for calculating the flow field quantities including all the flow and thermal properties as functions of temporal and spacial coordinates. The results also include the analysis of shock waves propagating both upstream and downstream from the cavity as well as the heated slug of laser gas bounded by two contact surfaces overriding the recirculating flow in the circulator. Samples of the numerical results are presented graphically and also in tabular form as shown in Figure 11 and Table I and IA,



respectively. These results demonstrate the capability of the program to numerically simulate the flow phenomena with a reasonable accuracy and a considerable flexibility for varying system parameters such as energy input, cavity dimensions, circulator dimensions and gas properties, provided that coefficients associated with the parameters are properly selected.

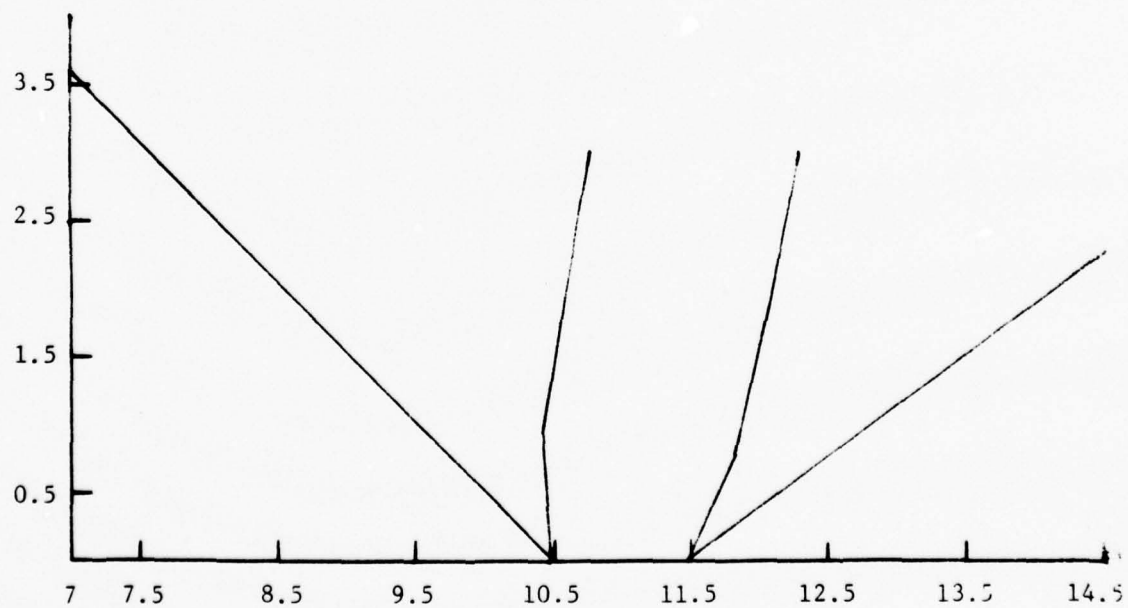
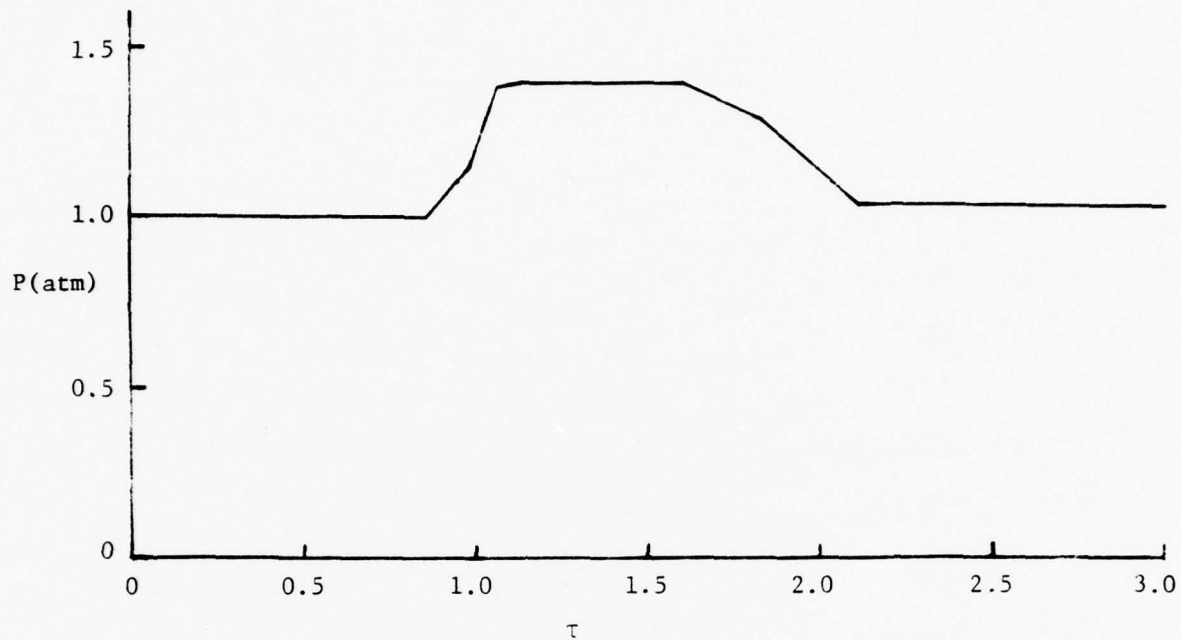


FIGURE 11. GRAPHICAL PRESENTATION OF A TYPICAL NUMERICAL SOLUTION FOR TRANSIENT FLOWS IN THE CIRCULATOR,

TABLE I

$\varepsilon$	$\tau$	U	$\alpha$	S	D	P	$\rho$	T
.9025+01	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.921+01	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.9361+01	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.9504+01	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.964+01	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.978+01	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.9922+01	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.1007+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.1015+02	.3744+00	-.6440-01	.105+01	.256-02	.250+00	.293+04	.295-02	.579+03
.102+02	.3744+00	-.6440-01	.105+01	.256-02	.250+00	.293+04	.295-02	.579+03
.1041+02	.3702+00	-.6440-01	.105+01	.256-02	.250+00	.293+04	.295-02	.579+03
.1055+02	.3600+00	-.6440-01	.129+01	.104+01	.250+00	.352+04	.234-02	.877+03
.1071+02	.3503+00	-.6440-01	.129+01	.104+01	.250+00	.352+04	.234-02	.877+03
.1085+02	.2551+00	-.6440-01	.129+01	.104+01	.250+00	.352+04	.234-02	.877+03
.1100+02	.3204+00	.1749+00	.134+01	.104+01	.250+00	.379+04	.234-02	.943+03
.1115+02	.2551+00	.4141+00	.129+01	.104+01	.250+00	.293+04	.195-02	.877+03
.1132+02	.3603+00	.4141+00	.129+01	.104+01	.250+00	.293+04	.195-02	.877+03
.1145+02	.3600+00	.4141+00	.129+01	.104+01	.250+00	.293+04	.195-02	.877+03
.1172+02	.3702+00	.4141+00	.105+01	.256-02	.250+00	.293+04	.295-02	.579+03
.1185+02	.3602+00	.4141+00	.105+01	.256-02	.250+00	.293+04	.295-02	.579+03
.11+02	.3744+00	.4141+00	.105+01	.256-02	.250+00	.293+04	.295-02	.579+03
.1207+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.1222+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.123+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.1250+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.1265+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.127+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.127+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.1307+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03
.1327+02	.4286+00	.1749+00	.100+01	.000	.250+00	.212+04	.234-02	.527+03

TABLE IA

E =	11.200	T0 =	.000	U =	.175	P =	3787.140	R0 =	.002340	T =	943.060
E =	11.200	T0 =	.107	U =	.175	P =	3787.146	R0 =	.002340	T =	943.060
L =	11.200	T0 =	.225	U =	.200	P =	3697.910	R0 =	.002299	T =	936.123
E =	11.200	T0 =	.338	U =	.340	P =	3199.650	R0 =	.002071	T =	897.389
E =	11.200	T0 =	.506	U =	.292	P =	2615.866	R0 =	.001943	T =	844.155
E =	11.200	T0 =	.675	U =	.175	P =	2702.214	R0 =	.001937	T =	812.928
E =	11.200	T0 =	.815	U =	.175	P =	2702.213	R0 =	.001937	T =	812.928
E =	11.200	T0 =	.955	U =	.175	P =	2702.213	R0 =	.001937	T =	812.928
E =	11.200	T0 =	1.093	U =	.175	P =	2702.212	R0 =	.001937	T =	812.928
E =	11.200	T0 =	1.232	U =	.173	P =	2700.199	R0 =	.001937	T =	812.322
E =	11.200	T0 =	1.373	U =	.169	P =	2623.712	R0 =	.001907	T =	801.520
E =	11.200	T0 =	1.514	U =	.175	P =	2606.740	R0 =	.001899	T =	800.061
E =	11.200	T0 =	1.628	U =	.287	P =	2703.347	R0 =	.001899	T =	829.388
E =	11.200	T0 =	1.737	U =	.175	P =	2633.500	R0 =	.001986	T =	829.375
E =	11.200	T0 =	1.877	U =	.175	P =	3005.033	R0 =	.002052	T =	851.632
E =	11.200	T0 =	2.017	U =	.175	P =	2655.971	R0 =	.001918	T =	806.424
L =	11.200	T0 =	2.159	U =	.175	P =	3137.161	R0 =	.002103	T =	868.744
E =	11.200	T0 =	2.300	U =	.172	P =	2705.597	R0 =	.001938	T =	812.469
E =	11.200	T0 =	2.441	U =	.172	P =	3037.197	R0 =	.002066	T =	855.415
L =	11.200	T0 =	2.582	U =	.180	P =	2649.794	R0 =	.001990	T =	832.207
E =	11.200	T0 =	2.719	U =	.181	P =	2621.645	R0 =	.001979	T =	828.679
E =	11.200	T0 =	2.861	U =	.184	P =	2995.425	R0 =	.002045	T =	851.762
E =	11.200	T0 =	3.001	U =	.175	P =	2625.095	R0 =	.001906	T =	802.416



Chapter IV

NUMERICAL ANALYSIS OF STEADY FLOWS IN THE  
CLOSED CYCLE CIRCULATOR

The overall program consists of the MAIN calling program which is aided by the ENPUT, GASP, AIRP, MACH, SIMQ, LIQP, and OUTPUT subroutines. Data transfer is conducted through common blocks VAR and IVAR. All of the real data is stored in VAR and the integer quantities are stored in IVAR.

Figure 1 illustrates the overall tunnel and coolant system, and identifies the assignment of station numbers referenced in the computer simulation.

#### DESCRIPTION OF THE COMPUTATIONAL PROCEDURE -

##### PRIMARY EMPHASIS ON MAIN AND ENPUT

At statement number two MAIN calls upon ENPUT to read in the NAMELIST case data and alphanumeric title. In the UAH simulations the control variable NTAM = 0, so that temperatures TA1, TIG, T02G, T06G, T07G, T1, T2, T3, T4, T6, T8, T10, T14, T16, T18, T20, and TA2 receive either specified input values or built-in values by default. Blower pressure ratio (BPR) and cavity inlet velocity (VI) are also obtained from input or default conditions. Cavity inlet pressure (PIG) is converted to psi, air relative humidity (RH) is converted to a decimal number, laser output efficiency (EFFL) is converted to a decimal number, and cavity inlet hydraulic diameter (DC), height (HI), width (WT1), and length (CL1) are all converted to feet. The AIRP subroutine is called with TA1, PAT, and RH so that air molecular weight will be available for the subsequent air density (R0A1) calculation for the radiator inlet. Air mass flow rate is next determined using R0A1, TA1, and the input value of corrected air volumetric flow rate (CWA). Fin thermal conductivities for all heat exchangers are converted into BTU/sec.-ft<sup>2</sup>-(°F/ft) and the number of coolant fluid passes in each heat exchanger is converted from integers to real numbers.

Although cavity inlet area is a routine input, it is again calculated from H1 and CL1. An estimate of the volumetric flow rate at tunnel station 6 is obtained from VI and A(1). The input list and case title are printed and control returns to MAIN.

With control again in MAIN, the following relationships provide starting estimates for certain tunnel static temperatures:

$$\begin{aligned}T2G &= T02G \\T5G &= T02G \\T6G &= T06G \\T10G &= T07G\end{aligned}$$

The loop counters JV and II are initialized at zero, and GASP is entered with TIG and FN providing values for GAMIG, CFIG, and GMU. The decision variable JCPR0 is consulted to determine whether cavity inlet pressure or density should remain fixed at its input value. If  $JCPR0 \geq 0$ , then

$$PIG = R01 * TIG / (.093178 * GMU)$$

if  $JCPR0 < 0$ , then

$$R01 = .093178 * PIG * GMU / TIG$$

Calculations for mass flow rate (WG), inlet Mach number (FM1), and inlet stagnation temperature (T01G) are now performed; and T01G serves as an estimate for the static temperature at tunnel station 11 (T11G). The AMT and BMT arrays are set to zero and heat exchanger calculations begin.

In the following, only calculations related to the first tunnel heat exchanger (HX1) will be outlined, since the calculation pertinent to (HX2), (HX3), and the outside radiator assembly are essentially similar.

On the coolant side of the heat exchanger, the bulk average temperature (TMI) is determined from the arithmetic average of the inlet and outlet temperatures:

$$TMI = .5*(T2 + T4)$$

On the gas side of the heat exchanger, the bulk average temperature (TGMI) is defined as the log-mean average temperature determined from:

$$TGMI = TMI + (Z1 - Z2)/(ln Z1 - ln Z2)$$

where  $Z1 = T5G - T4$

and  $Z2 = T6G - T2$

However, if either Z1 or Z2 = 0., then

$$TGMI = .5* (T5G + T6G)$$

GASP is now entered with TGMI and FN, and it provides the constant pressure specific heat (CPGI), Prandtl Number (PRGI), viscosity (GIMU), and molecular weight (GMU). LIQP is similarly called with TMI and FG, providing the coolant viscosity (ZIMU), Prandtl Number (PRI), and specific heat (CPI).

The gas side overall frontal area (AFRGI) is given by

$AFRGI = DL(1) * DH(1)$ , and the gas stream mass velocity (GGI) is determined from

$$GGI = WG/(DSIG(1) * AFRGI)$$

where DSIG(1) represents the dimensionless ratio of free-flow area to frontal area.

For the coolant side, the overall frontal area per pass (AFRI) is given by



$$AFRI = DW(1) * DH(1)/DNP(1)$$

The coolant stream mass velocity (GI) is determined from

$$GI = WI/(DSI(1) * AFRI)$$

where WI is the input value of coolant mass flow rate and DSI(1) is the dimensionless ratio of free-flow area to frontal area.

Representative Reynolds Numbers for the gas side (REGI) and coolant side (REI) are given by

$$REGI = GGI * DDHG(1)/GIMU$$

$$REI = GI * DDH(1)/ZIMU$$

For the gas side, the data on Figure 2 was employed in the construction of functions expressing the dependence of the mean friction factor (GFI), and the Colburn J factor (GJI), on REGI. For the liquid side, the Colburn J factor (ZJI) was related to REI on the basis of the data presented in Figure 3.

It should also be noted that the three heat exchangers have identical plate-fin core structures, whereas the gas side data for a radiator is presented in Figure 4. The coolant side plate-fin structure of a radiator is identical to that of the three tunnel heat exchangers. Coolant friction factors were not computed, since current UAH simulations do not examine pressure drops in the coolant circulation system.

The unit conductances for the thermal convection heat transfer on the gas side (HGI) and on the liquid side (HI) are given by

$$HGI = GGI * CPGI * GJI * (PRGI)^{-2/3}$$

$$HI = GI * CPI * ZJI * (PRI)^{-2/3}$$

The fin effectiveness parameters on the gas and coolant sides are denoted by GMI and GML, respectively.

$$GMI = \frac{2 * HGI}{DK(1) * DDEL(1)}$$

where DDEL (1) represents the gas side fin thickness in feet. Similarly,

$$GML = \frac{2 * HI}{DK(1) * DA(1)}$$

where DA(1) represents the liquid side fin thickness in feet. It should also be noted that the identical thermal conductivities used in the expressions for GMI and GML imply that fins on both sides of the heat exchanger are constructed from the same material (currently aluminum).

Since the fins extend from wall-to-wall, it has been assumed that the effective fin length is given by one half of the wall spacing. On the gas side, the fin efficiency (ATFI) is given by

$$ATFI = \frac{TANH[GMI*DSL(1)]}{GMI * DSL(1)}$$

where DSL(1) represents the gas side fin length in feet. Similarly, the liquid side fin efficiency (ATFIL) is computed from

$$ATFIL = \frac{TANH[GML*DSLL(1)]}{GML * DSLL(1)}$$

where DSLL(1) represents the liquid side fin length in feet.

The total surface temperature effectiveness of the heat transfer surfaces on the gas side (ATØ1) is given by the weighted average of the 100% effectiveness of the prime surface and the less effective fin surface.

$$ATØI = 1.-DAFØA(1) * (1.-ATFI)$$

where DAFØA(1) represents the ratio of fin area to surface area.

On the liquid side, the total temperature effectiveness (ATØ1) is computed from

$$AT\emptyset 1 = 1.- DAFAL(1) * (1.-ATFIL)$$

where DAFAL(1) represents the ratio of fin area to surface area.

The overall conductance for heat transfer for the first heat exchanger (UI) is given by

$$UI = 1./ (1./ (AT\emptyset I * HGI) + AB(1)/DK(1) * (1.-DAF\emptyset A(1))) + DALG(1)/(DALF(1) * HI * AT\emptyset 1))$$

where AB(1) represents the parting plate thickness in feet, DALG(1) is the gas side heat transfer surface area to volume ratio in 1/ft., and DALF(1) is the ratio of liquid side heat transfer surface area to volume in 1/ft.

In the final calculations related to the heat exchanger effectiveness estimation, the coolant and hot gas capacity rates are evaluated and compared to establish the appropriate minimum and maximum values identified by CMINI and CMAXI, respectively. Having defined AGI as the surface area on which UI is based, the number of heat transfer units (TUNI) is now given by

$$TUNI = AGI * UI/CMINI$$

The heat exchangers and radiators have been assumed to correspond to the multipass overall-counterflow configuration; and the number of coolant passes in each unit is contained in the DNP array. Kays and London (Reference 1) have observed that the effect on performance of fluid mixing, either within passes or between passes, is not significantly different from cases where there is no mixing at all, hence the single-pass effectiveness (ESSI) is computed from

$$ESSI = 1.-EXP - T\emptyset WI * CMAXI/CMINI$$

where

$$T\theta WI = 1. - \text{EXP} - TUNI * CMINI / (CMAXI * DNP(1))$$

The overall effectiveness (EPSI) is now given by the following sequence of calculations

$$EPSI = ((1. - ESSI * CMINI / CMAXI) / (1. - ESSI)) ** NP(1)$$

$$EPSI = (EPSI - 1.) / (EPSI - CMINI / CMAXI)$$

However, if CMINI/CMAXI is greater than .9999, then

$$EPSI = DNP(1) * ESSI / (1. + ESSI * (DNP(1) - 1.))$$

Tunnel calculations continue with the determination of station 1 stagnation pressure using known values for Mach number, specific heat ratio, and static pressure. Since the cavity design control parameter NDSGN was always set at a value of two, the calculations are forced to assume a constant area cavity. Although A(2) is an external input, it is now set equal to the cavity inlet area. Assuming constant specific heat for the gas flowing in a heated duct, the temporary variable Z1 representing stagnation temperature for a choked/heated cavity at a station where the Mach number is postulated equal to one, is obtained from

$$Z1 = \frac{T\theta 1G * (1. + GAMIG * FMI^2)^2}{2 * (GAMIG + 1.) * FMI^2 * 1. + \frac{GAMIG - 1.}{2} * FMI^2} \equiv T_o^*$$

Next, Z1 is redefined as  $T\theta 2G / T_o^*$ ; and if  $Z1 > 1$  the message "Choked Cavity-Read New Data" is printed and the case is aborted.

If the test on Z1 was satisfactory, then the static temperature loop counter is initialized at a value of zero and GASP is entered with known values of T2G and FN. GASP returns values for GAM2G, CP2G and GMU (which is fixed for the case since it only depends upon the gas mixture specified initially).



Under the assumption that  $GAMIG \approx GAM2G$

$$\frac{T02G}{T_o^*} = \frac{2 (\gamma_2 + 1) M_2^2 \left(1 + \frac{\gamma_2 - 1}{2} M_2^2\right)}{(1 + \gamma_2 M_2^2)^2} = Z1$$

where  $\gamma_2$  and  $M_2$  have been employed as shorthand forms for  $GAM2G$  and  $FM2$ , respectively. This convention will also be adopted for other tunnel stations. Upon defining

$$Z2 \equiv 2 \gamma_2 Z1 - 2 \gamma_2 - 2$$

and

$$Z3 \equiv \gamma_2^2 (Z1 - 1) + 1$$

we obtain the following equation that must be satisfied by  $M_2$

$$Z3 (M_2^2)^2 + Z2 M_2^2 + Z1 = 0$$

Finally,  $M_2$  is given by the square root of a positive solution  $\leq 1$  determined for the above equation. However, if  $Z3 = 0$ , then  $M_2$  is simply determined from

$$M_2 = \frac{-Z1}{Z2}$$

The current value of  $T2G$  is now stored as the variable  $T2G0LD$ , and a new value of  $T2G$  is computed from

$$T2G = \frac{T02G}{1 + M_2^2 \frac{\gamma_2 - 1}{2}}$$

If the new value of  $T2G$  is within a .5 degree (Rankine) neighborhood of  $T2G0LD$ , then the solution continues. If  $T2G$  does not pass this test but the loop counter has not been exceeded, then the static temperature loop

is reentered at statement number 12000 using the current value of T2G. If the above two conditions have not been satisfactorily met, then the message "Failure to Converge in Static Temp. Loop 1" is printed, also recording the temperature error and number of loop cycles. The run is subsequently aborted.

A successful pass through the above criteria is followed by the computation of static (P2G) and stagnation (P02G) pressures at the cavity exit.

Using the fixed value of total pressure loss coefficient (CF23) for the first diffuser, the exit stagnation pressure is given by

$$P03G = P02G - CF23*(P02G-P2G)$$

Using estimated values of  $\gamma_3$  and  $M_3$  the MACH subroutine is called in conjunction with known values for DELM, NLIM, P03G, T03G = T02G, WG, GMU, A(3), and FN. Internally, MACH calls upon GASP to provide values for  $C_p$  (T) and  $\gamma$  (T); and MACH iterates on  $M_3$  until a value of  $M_3$  is found that lies within DELM of the  $M_3$  computed on the previous pass through MACH. By-products of the MACH subroutine are values of GAM3G, CP3G, static temperature, and static pressure at station 3.

It should be noted that since  $\gamma_3$  is computed after MACH number convergence, "convergence" in MACH is actually obtained with slightly inconsistent values of T3G and  $\gamma_3$ . If the number of iterations in the MACH subroutine equals NLIM and convergence has not been obtained then the error message, "Failure to Converge in MACH No. Subroutine", along with the error value, is printed; and control returns to the main program (the run is not aborted).

With the assumption that stagnation temperature from station 2 to station 5 is constant, the calculations for gas flow properties at stations

4 and 5 are obtained in a manner analogous to the calculations performed for station 3.

The density at station 5 (R05) is given by

$$R05 = .093178 * P5G * GMU/T5G$$

The counter for Density Loop 1 is initialized at a value of zero and initial estimates for R06, M<sub>6</sub>, and γ<sub>6</sub> are obtained from

$$\begin{aligned} R06 &= R05 \\ GAM6G &= GAM5G \end{aligned}$$

$$FM6 = WG * DSQRT(T06G/GAM5G/GMU) / (20.7774 * P05G * A(6))$$

The value of R06 is stored in the dummy variable Z1 and the stagnation pressure at station 6 is predicted from

$$\begin{aligned} P06G &= P05G - GGI^2 * ((1. + DSIG(1))^2) * (R05/R06 - 1) + GFI * DALG(1) * DW(1) * \\ &R05 / (.5 * DSIG(1) * (R06 + R05)) / 9266.11 * R05 \end{aligned}$$

Having T06G and P06G, MACH is called to provide values for the static temperature and static pressure at station 6. These values are used to compute a new value for R06. The absolute value of the dummy variable Z3 = R06 - Z1 is compared with R0LIM, to determine if convergence has been attained. If the comparison is not satisfactory and the loop counter is less than NLIM, then the loop is reentered with the current value of R06. If the loop counter equals NLIM and convergence has not been obtained, then the error message "Failure to Converge in Density Loop 1" is printed. The error is also recorded and the run is not aborted. For situations of satisfactory convergence, the message "Density Loop 1-cycles (number of passes through loop) - error (Z3)" is printed and calculations continue.

Using the current value of  $T_{07G}$  as an approximation for  $T_{7G}$ , and a subsequent call to GASP, results in an approximation for  $GAM_{7G}$ . The stagnation pressure at station 7 ( $P_{07G}$ ) is computed from

$$P_{07G} = P_{06G} * BPR$$

and the counter for the pressure loop is initialized at a value of 0. The MACH number at station 7 ( $FM_7$ ) is estimated from

$$FM_7 = WG * DSQRT \quad T_{07G} / (GAM_{7G} * GMU) \quad / (20.7774 * P_{07G} * A(7))$$

The estimates of  $FM_7$  and  $GAM_{7G}$  plus other currently known quantities are used with a call to the MACH subroutine, whose convergence yields a value for the static pressure at tunnel station 7 ( $P_{7G}$ ). To go from station 7 to station 8, the heat exchanger equations are solved for the third heat exchanger. Since the diffuser pressure loss coefficient  $CF_{89}$  is a known quantity, the stagnation pressure at tunnel station 9 ( $P_{09G}$ ) is computed from

$$P_{09G} = P_{08G} - CF_{89} * (P_{08G} - P_{8G})$$

Under the assumption of a constant stagnation temperature existing between stations 8 through 11, the above technique is also exploited in the successive evaluation of corresponding flow properties for stations 9 through 10. The density for station 10 ( $R_{010}$ ) is given by

$$R_{010} = .093178 * P_{10G} * GMU / T_{10G}$$

Starting estimates are obtained for the MACH number  $FM_{11}$  and density ( $R_{011}$ ) at station 11; and the counter for the second density loop is initialized at a value of zero.

The value for  $R_{011}$  is also stored in the dummy variable  $Z_1$ , and the stagnation pressure at station 11 ( $P_{011G}$ ) is given by



$$P011G = P010G - GGII^2 * ((1. + DSIG(2)^2) * (R010/R011 - 1.) + GFI * DALG(2) * DW(2) * R010 / (.5 * DSIG(2) * (R010 + R011))) / (9266.11 * R010)$$

A call to the MACH subroutine, assuming that  $T011G = T01G$  and letting  $GAM10G$  be an initial estimate for  $GAM11G$ , results in values for  $T11G$ ,  $P11G$ ,  $FM11$ ,  $GAM11G$ , and  $CP11G$ , upon convergence.

A new value for  $R011$  is now computed from

$$R011 = .093178 * P11G * GMU / T11G$$

and the dummy variable  $Z3$  is defined by

$$Z3 = R011 - Z1$$

The absolute value of  $Z3$  is compared with  $R0LIM$  to determine if convergence has occurred in the density loop. If  $|Z3| > R0LIM$  and the current value of the loop counter is less than  $NLIM$ , then the loop is reentered with the present value of  $R011$ . If the loop counter equals  $NLIM$  and convergence has not been attained, then the error message "Failure to Converge in Density Loop-2" is printed. The error is also recorded and the run is not aborted. For situations of satisfactory convergence, the message "Density Loop-2-Cycles (number of passes through loop) - Error = (Z3)" is printed and system calculations resume.

Next,  $FM11$  is reestimated from other known quantities:

$$FM11 = WG * DSQRT(T01G / (GAM1G * GMU)) / (20.7774 * P011G * A(11))$$

and the MACH subroutine is again called to provide refined values of  $T11G$ ,  $P11G$ ,  $FM11$ ,  $GAM11G$ , and  $CP11G$ .

If the decision variable  $JCPR0 \geq 0$ , then a new dummy variable  $Z1$  is defined by

$$Z1 = R01 * TIG / (.093178 * GMU) * (1. + (GAMIG - 1.) * FMI^2 / 2) ** (GAMIG / (GAMIG - 1.))$$

and subsequently, Z1 becomes

$$Z1 = P011G - CF111 * (P011G - P11G) - Z1$$

However, if JCPR0 < 0, then the variable Z1 is defined by

$$Z1 = P011G - CF111 * (P011G - P11G) - P01G$$

Note that if Z1 > 0 there is an implied overshoot of inlet stagnation pressure as determined by the flow conditions at station 11. Since Z1 will probably never turn out identically zero in the computations, flow stagnation pressure adjustments are necessary:

$$P011G = P011G - Z1$$

$$P010G = P010G - Z1$$

$$P009G = P009G - Z1$$

$$P008G = P008G - Z1$$

$$P007G = P007G - Z1$$

The known static temperature at station 6 is used with a call to subroutine GASP so that values will be available for GAM6G and CP6G.

The desired blower pressure ratio (BPR) can now be computed from

$$BPR = P007G / P006G$$

and the volumetric flow at station 6 (Q6G) is determined from

$$Q6G = 60. * A(6) * FM6 * DSQRT(GAM6G * T6G * 32.174 * 1545.43 / GMU)$$

Having specified the volumetric flow rate, the number of blower sets, and the blower rpm, the blower polytropic efficiency (ATAB) is given by

$$ATAB = .73 - 7.09843 * (DABS(Q6G/BRPM/NBS - .5355)) ** 2.08014$$

The above efficiency function is also presented in Figure 5.

Hence, T07G can be recomputed from

$$T07G = T06G * (BPR ** ((GAM6G - 1.) / (ATAB * GAM6G)))$$

The pressure loop counter J is incremented by one, and the magnitude of the stagnation pressure error at station 11 is compared with the pressure error tolerance PLIM. If  $|Z1| < PLIM$ , then calculations resume at statement number 85. If  $|Z1| \geq PLIM$  and  $J < NLIM$ , then the pressure loop repeats itself from statement 80. Alternatively, if  $J = NLIM$  and a pressure error still exists, then the message "Failure to Converge in Pressure Loop-Error = Z1" is written and the calculations continue at statement 85, where AIRP is called to determine the constant pressure specific heat of ambient air. The message "Total Passes Through Pressure Loop = (value of J) - Error = (value of Z1)" is next recorded.

Subroutine AIRP is called to determine the constant pressure specific heat and specific heat ratio for radiator exhaust air. Similarly, subroutine LIQP is called 11 times to establish specific heats associated with the coolant temperatures existing at the various reference locations. Until the call to SIMQ, all subsequent calculations are associated with the determination of the values for the elements of the 18 by 18 [AMT] matrix and the 18 x 1 [BMT] matrix used in performing the simultaneous solution of all system temperatures.

The matrix equation  $[AMT] \bar{X} = [BMT]$  denotes the 18 equations used to establish energy balances across system components expressing a change in enthalpy between entering and leaving fluid streams. Energy balances across the heat exchangers and radiators are supplemented by effectiveness/

temperature change relationships. The elements of the [AMT] and [BMT] matrices are identified in Table II, and the 18 x 1 solution vector returned by SIMQ is an updated estimate for the following temperatures: T01G, T02G, T06G, T07G, T1, T2, T3, T4, T6, T8, T10, T14, T16, T18, T20, TA2, T08G, and T7.

It should be noted that the equivalence statement preceeding statement number 2 in the MAIN program immediately loads the elements of  $\bar{X}$  into the appropriate locations of COMMON VAR. Hence, each time SIMQ is called by MAIN all the sytem temperatures represented in the vector  $\bar{X}$  are updated.

The Final Mach Loop counter JJ is initialized at a value of zero and the dummy variable Z2 is set equal to FML.

The cavity inlet static temperature is now determined from the revised inlet stagnation temperature

$$TIG = BMT(1)/(1.+(GAMIG-1.)*FML^2/2.)$$

and GASP is called to provide values for GAMIG and CPIG consistent with TIG.

If  $JCPR0 \geq 0$ , then the cavity inlet static pressure becomes

$$PIG = R01*TIG/ (.093178*GMU)$$

If  $JCPR0 < 0$ , then the cavity inlet density is given by

$$R01 = .093178*PIG*GMU/TIG$$

The gas mass flow rate (WG) is determined from

$$WG = R01*VI*A(1)$$



and a new cavity inlet MACH number is given by

$$FM1 = WG*DSQRT(TIG/(GAMIG*GMU))/(20.7774*PIG*A(1))$$

The counter JJ is incremented by one and the dummy variable Z3 is defined by

$$Z3 = Z2 - FM1$$

If the absolute value of Z3 is less than DELM then calculations resume at statement 7. If MACH number convergence has not been attained and  $JJ < NLIM$ , then the current value of FM1 is used in reentry of the Final Mach Loop at statement 6. However, if the MACH number is not within tolerance and  $JJ = NLIM$ , then the message "Failed to Converge in Final Mach Loop - Error = (value of Z3)" is written and calculations again reach statement 7. Statement 7 writes the message "Total Passes in Final Mach Loop = (value of JJ) - Error = (value of Z3)".

If the value of the error indicator KS defined in SIMQ is one, the program goes to statement 91 and writes the error message "Singular Matrix" and aborts the case.

The eighteen elements in the array NN are set equal to -1, and

$$TDIF(KS) = SVR(KS) - BMT(KS)$$

where  $KS = 1, 2, \dots, 16$  is a new dummy variable, SVR is the array composed of system temperatures before calling SIMQ, and BMT is the system temperature array provided by the call to SIMQ.

If the absolute value of any of the elements in the TDIF array is greater than the corresponding value input into the temperature convergence tolerance array CONV, then the appropriate element in the NN array is set equal to one.

The temperature differences recorded in array TDIF are now presented under the heading of "State Variable Errors." The message "End of SIMQ Pass No. (value of II)" is recorded; and if  $II > NLIM$  then computations resume at statement 92 where the warning "Failure to Converge in State Variable Loop" is printed, and the solution continues at statement 90 without having guaranteed convergence on temperatures.

However, if  $II \leq NLIM$ , then each element of the NN array is examined to determine whether it is zero or positive. If any element of NN satisfies this test then calculations resume at statement 95, where the SVR array is reset with corresponding values from the BMT array, and the case repeats from statement 10. If all elements of NN fail this test, then the case continues at statement 90 where FM6 is estimated from

$$FM6 = WG * DSQRT(T06G / (GAM6G * GMU)) / (20.7774 * P06G * A(6))$$

This calculation is followed by a call to MACH so that convergence on FM6 can be obtained.

After converting the number of blower sets and the number of blowers per set from integers to real numbers, the cavity inlet velocity correction GC is determined via the following six equations

$$DPSS = ((P07G - P06G) * T06G * 28.966) / (P06G * BRPM * BRPM * 518.7 * GMU * FNBPS)$$

$$DPSB = .8396 - 3.2323 * (DABS(Q6G / (BRPM * FNBPS) - .46875)) ** / .42327$$

$$DPSB = DPSB * 1. E-9$$

$$ERR = DPSB - DPSS$$

$$GC = 11.661 E-7 / (BRPM * FNBPS) + 11.589 E-5 * VIM ** .667 / (BRPM * BRPM * FNBPS)$$

$$GC = ERR / GC$$

Note that the calculation of DPSB is derived from the empirical blower pressure data presented on Figure 5.

The velocity loop counter JV is incremented by one before the message "Pass No (value of JV) Through Velocity Loop, Correction = (value of GC)" is printed.

If  $|GC| \leq V_{LIM}$ , then calculations resume at statement number 502.

If  $JV \geq N_{LIM}$ , then calculations resume at statement number 503, where the error message "Failure to Converge in Velocity Loop-Error = (value of GC)" is recorded before calculations resume at statement number 502.

If  $GC < 0$  and  $Q6G/(BRPM*FNBS) < .46875$ , then the message "Blowers are Choked - Process Next Case" is printed and the run is aborted.

For all other situations, before repeating at statement number 501, the cavity inlet velocity is updated in the following manner

$$VIM = VIM + GC$$

$$VIM = VIM * 3.281$$

At statement number 502, the following revisions are made to chosen stagnation temperatures:

$$T03G = T02G$$

$$T04G = T02G$$

$$T05G = T02G$$

$$T08G = T07G$$

$$T09G = T07G$$

$$T010G = T07G$$

$$T011G = T01G$$

The blower power required in horsepower (BLPR) is given by  
$$BLPR = WG * .5 (CP6G + CP7G) * T06G * (BPR * ((1. - 2. / (GAM6G + GAM7G)) / ATAB) - 1.) * 778. / 550.$$

whose kilowatt equivalent (BLPRM) becomes

$$BLPRM = BLPR * .7457$$

It should also be noted that since this investigation centered on the recirculating laser gas flow in the wind tunnel, the coolant friction factors and pressure drops were not computed.

The radiator inlet air density ( $R\theta A1$ ) is computed from

$$R\theta A1 = 144.*PAT*AML/(1545.32*TA1)$$

The radiator exit air density ( $R\theta A2$ ) is initially assumed the same as the inlet air density and the radiator density loop counter (LL) is initialized at a value of zero. After setting the dummy variable  $Z1=R\theta A2$  the exit air static pressure (PA2) is computed from

$$PA2 = PAT - GA*GA*((1.+DSIG(3)**2)*(R\theta A1/R\theta A2-1.) + \\ AF*DALG(3)*DW(3)*R\theta A1/(.5*DSIG(3)*(R\theta A1+R\theta A2)))/ \\ (R\theta A1*2.*32.174*144.)$$

The outlet air density is now recomputed from

$$R\theta A2 = 144.*PA2*AML/(1545.32*TA2)$$

The loop counter is subsequently incremented by one and the dummy variable Z3 is defined by

$$Z3 = R\theta A2 - Z1$$

If  $|Z3| < R\theta LIM$ , then density convergence has been attained and the calculations resume at statement number 38. If  $|Z3| \geq R\theta LIM$  and  $LL \leq NLIM$  then the density loop is repeated at statement 37, using the



current value of  $R\theta A2$  as the initial guess in the loop. However, if  $LL = NLIM$ , then the error message "Failure to Converge in Aux. Density Loop - Error = (value of Z3)" is recorded before resuming at statement number 39. The run is not aborted.

When convergence on density has been attained, the message "Total Passes Through Aux. Density Loop = (value of LL) - Error = (value of Z3)" is printed before resuming calculations at statement number 39.

The fan power required in horsepower (PF) is given by

$$PF = WA * CPA2 * TA2 * ((PAT/PA2) ** ((1.1./GAM2A)/ATAP) - 1.) * 778./550.$$

whose kilowatt equivalent (PFM) becomes

$$PFM = PF * .7457$$

Tunnel gas density at station 6 ( $R\theta 6G$ ) is determined from

$$R\theta 6G = .093178 * P6G * GMU/T6G$$

and the corrected volumetric flow rate at this station ( $QC\theta RR$ ) is given by

$$QC\theta RR = 60. * WG * DSQRT(1.4 * GMU * 518.7 / (GAM6G * 28.97 * T\theta 6G)) / R\theta 6G$$

The elements of the SVR array are given values matching values in corresponding elements of the BMT array and the total heat transfer rate in BTU/HR for the first heat exchange (QDI) is computed from

$$QDI = WI * 1800. * (CP2 + CP4) * (T4 - T2)$$

The heat transfer rates for the second and third heat exchanger and radiator system are given, respectively, by



$$QDII = WII * 1800 . * (CP2+CP6)*(T6-T2)$$

$$QDIII = WIII * 1800 . * (CP2+CP7)*(T7-T2)$$

$$QDA = W3 * 1800 . * (CP3+CP1)*(T3-T1)$$

The complete program flow charts are presented in Table II. An Input List for a typical example and the corresponding Output Results are presented in Table III. Appendix D presents the Program Listing.

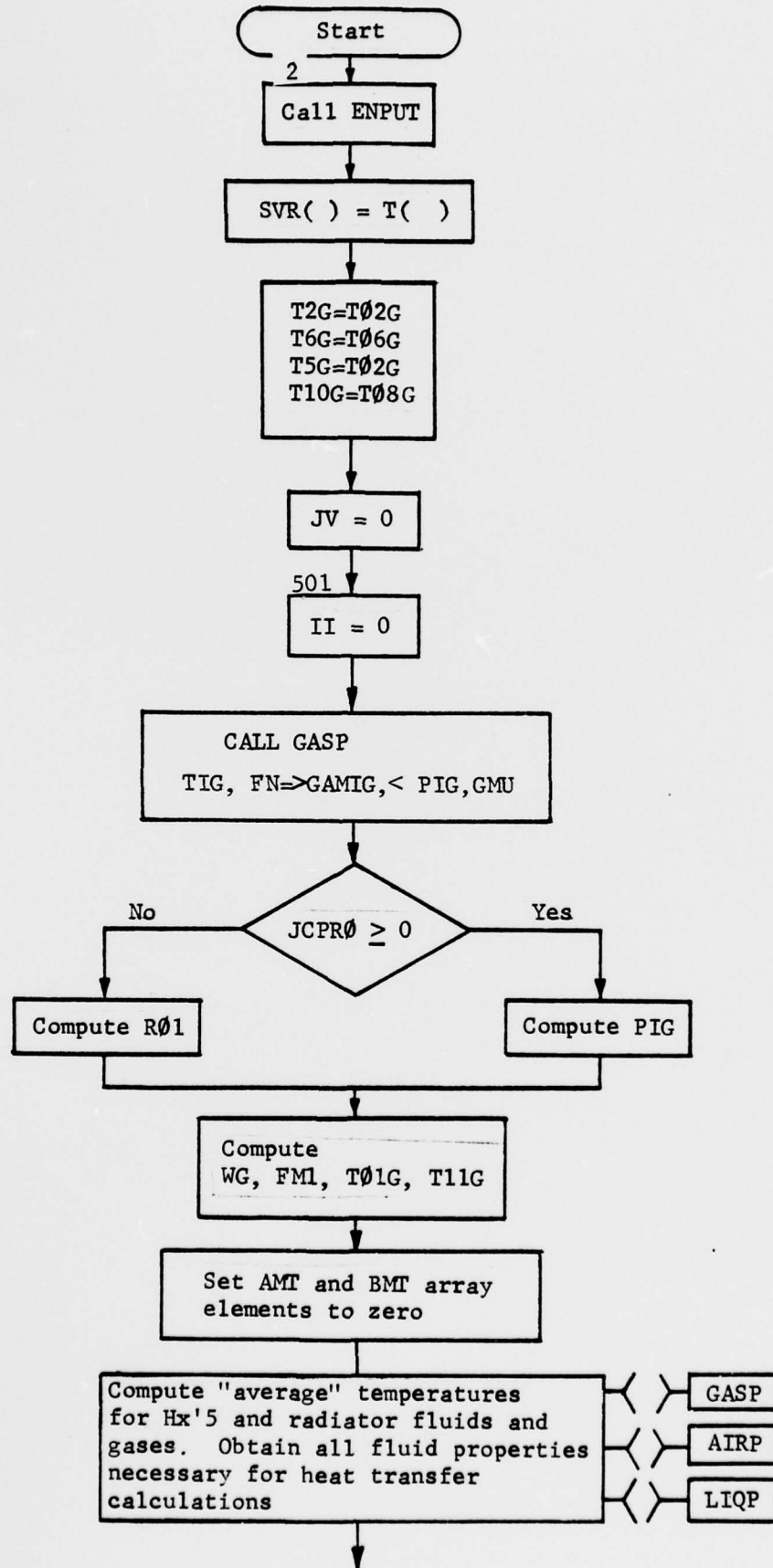
Appendix E presents some sample results obtained for flow variables around the system for the case of three heat exchangers. We show the results for static temperature (Figure E1), total temperature (Figure E2), density (Figure E3), static pressure (Figure E4), total pressure (Figure E5), velocity (Figure E6), and Mach number (Figure E7). The results are for the following:

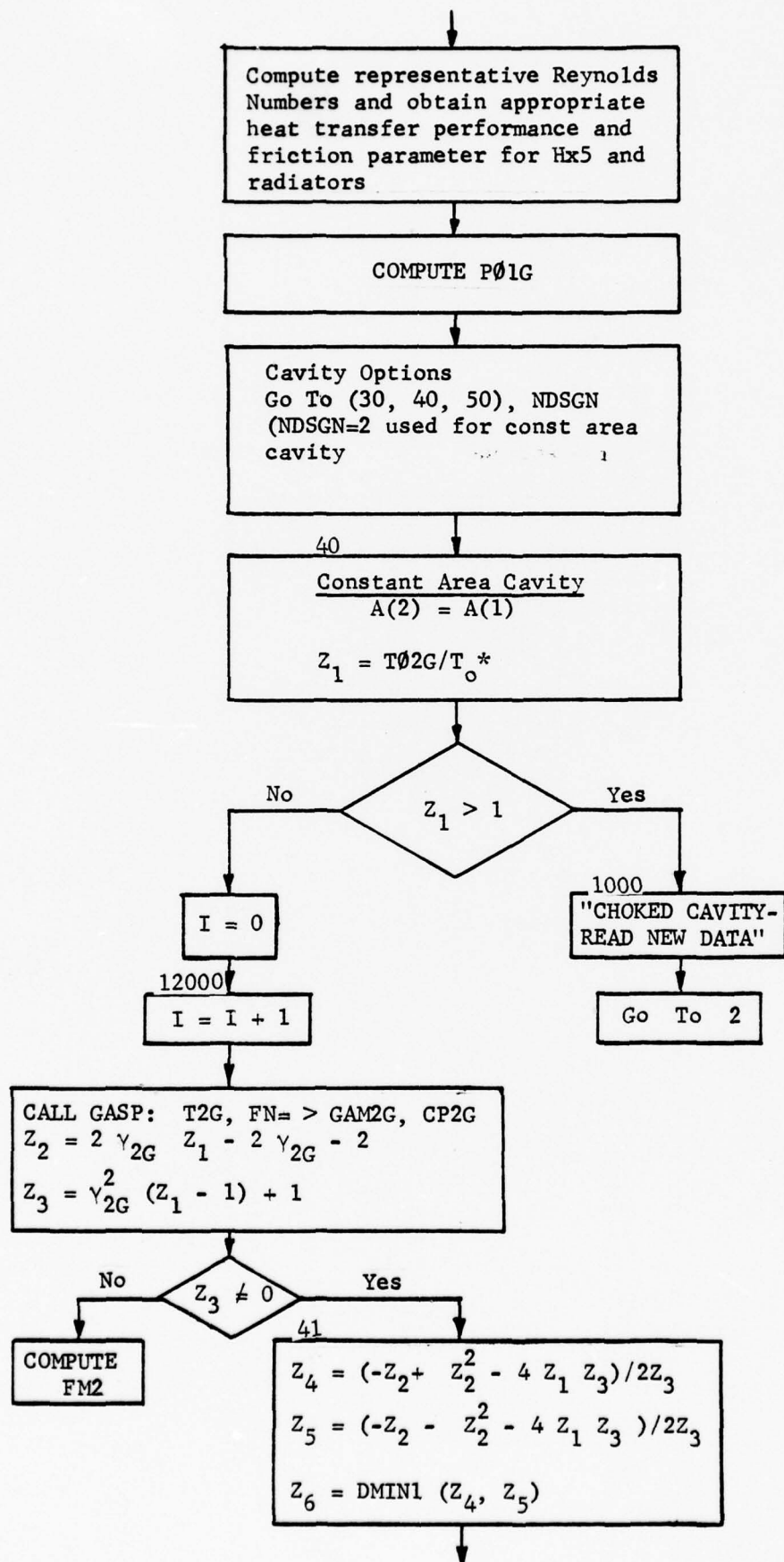
$$PLKW = 50$$

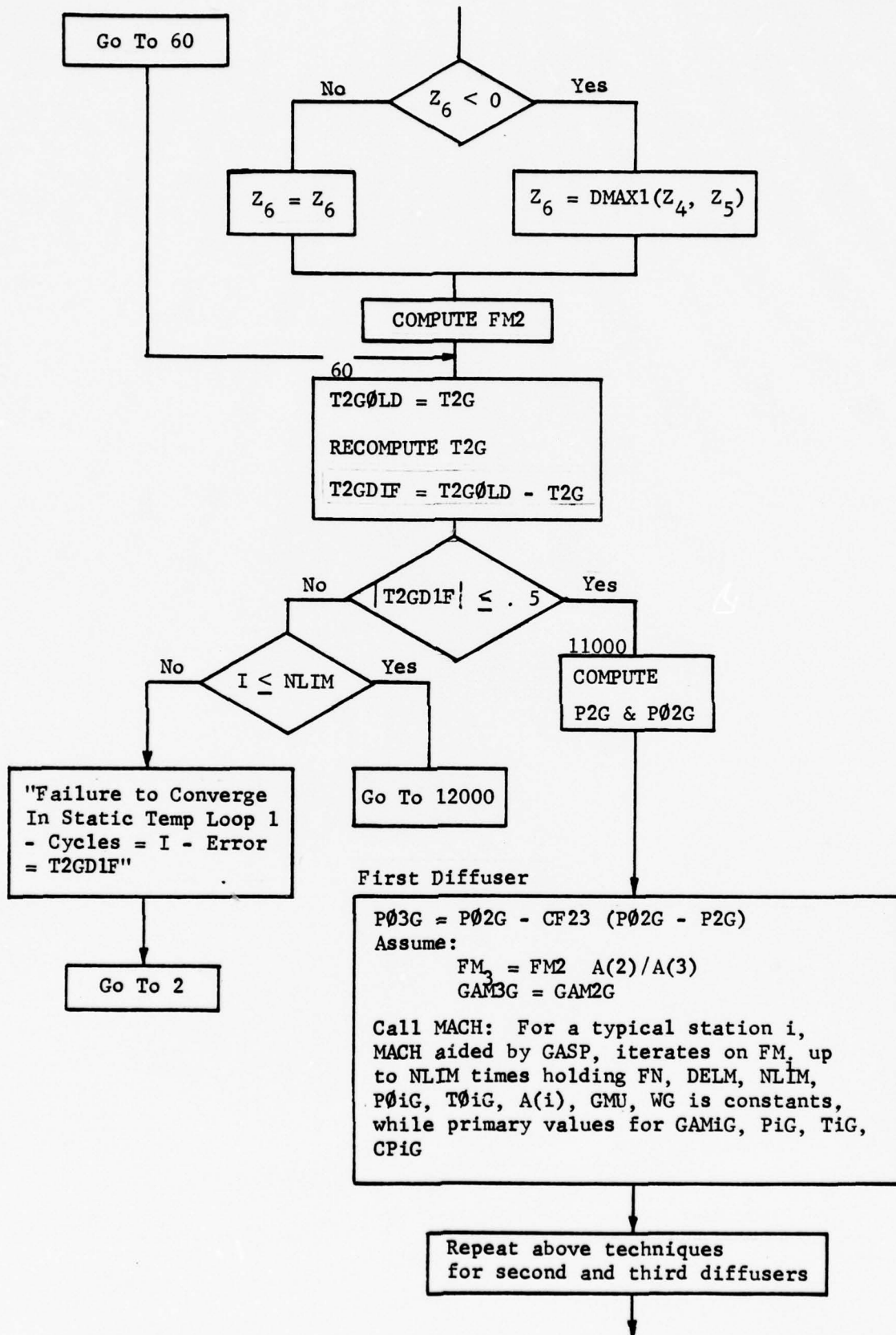
$$PIGA = 1$$

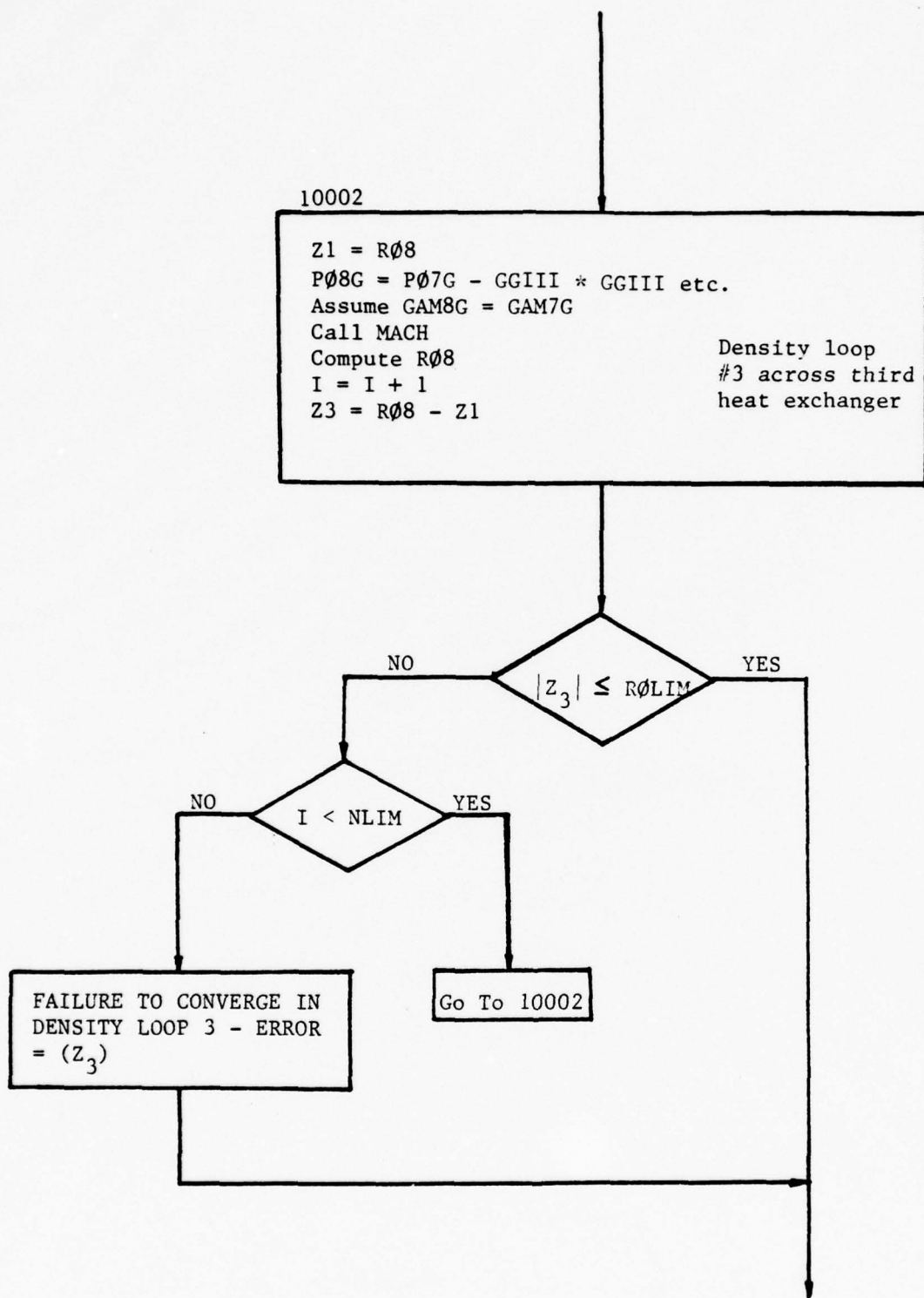
$$TA1F = -50$$

TABLE II

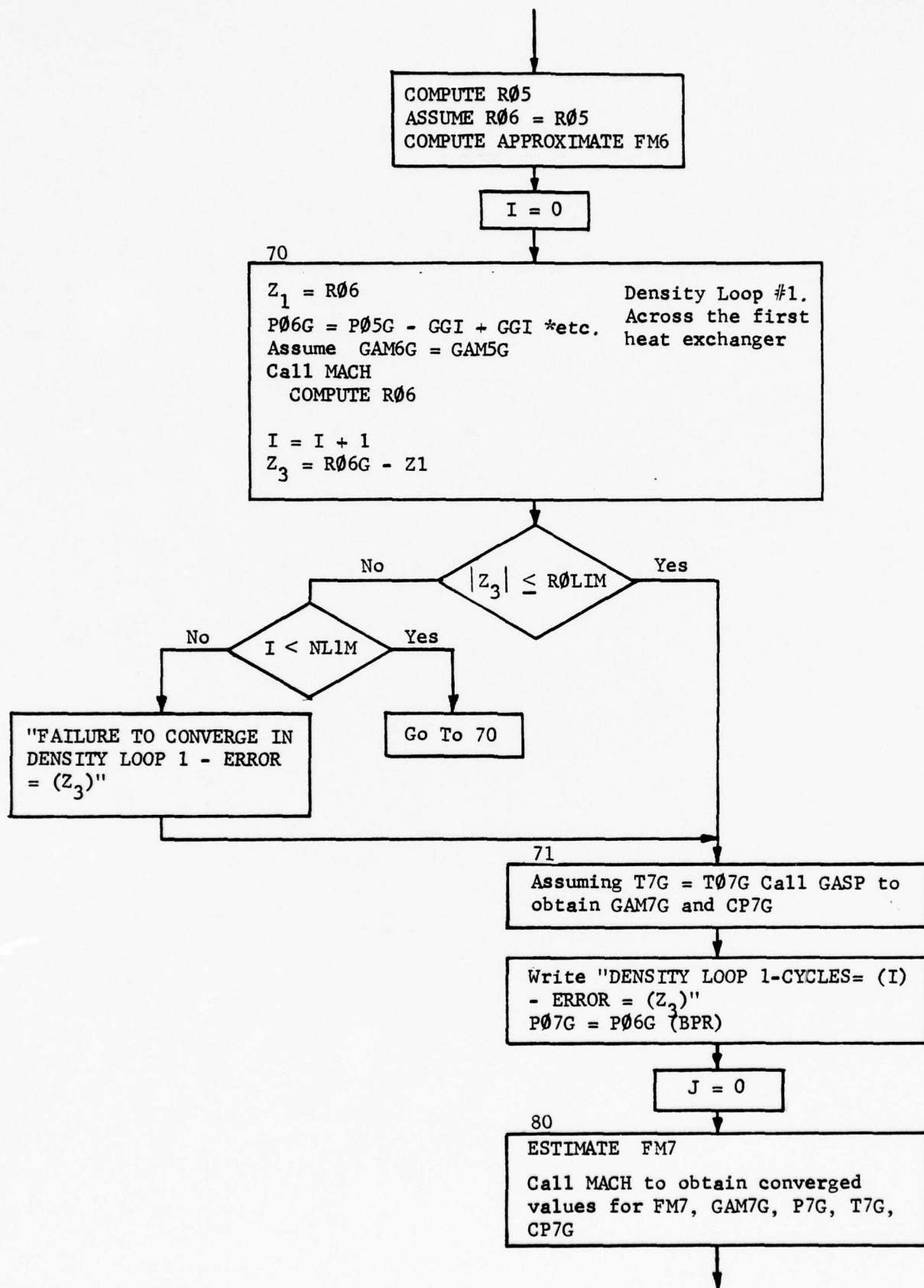


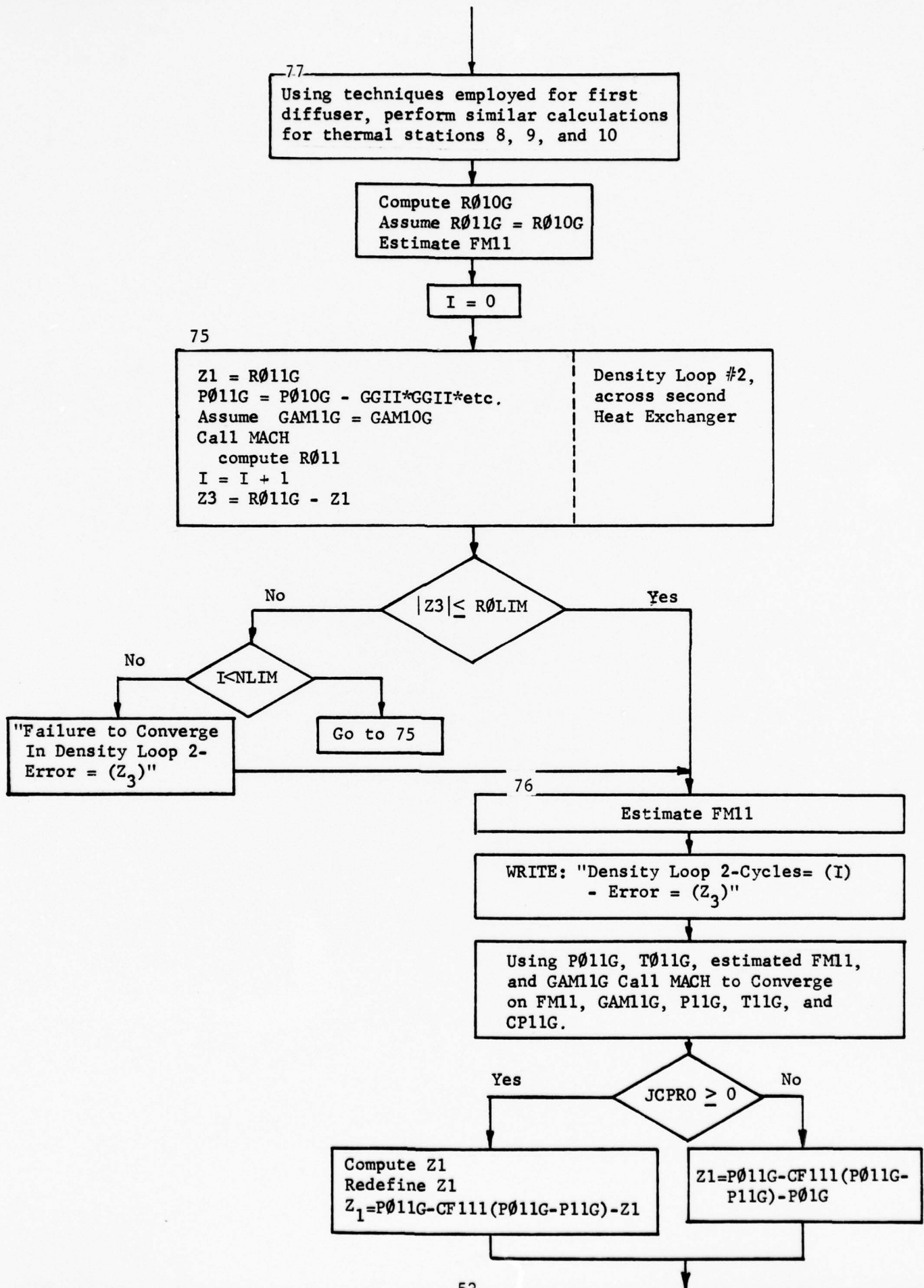


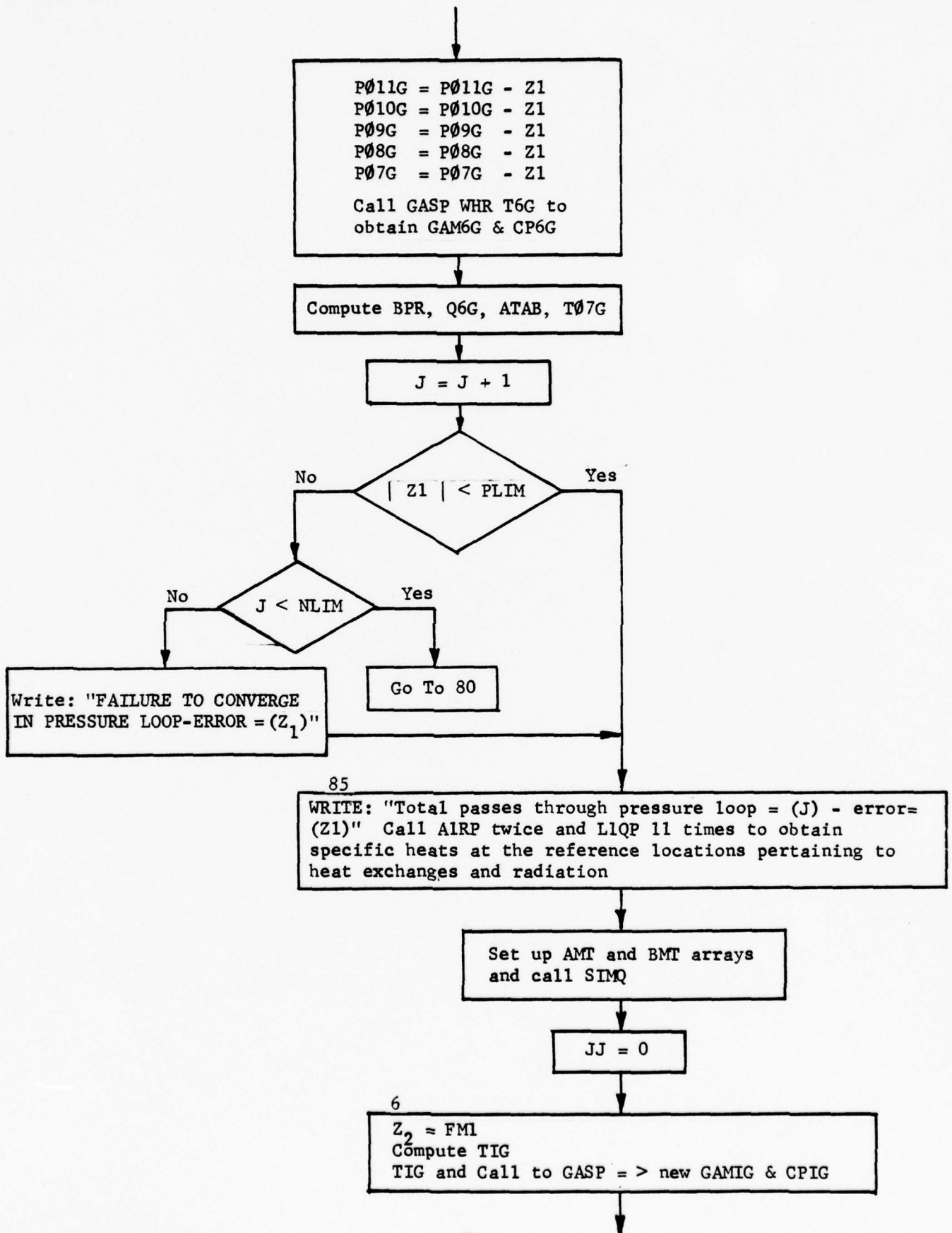


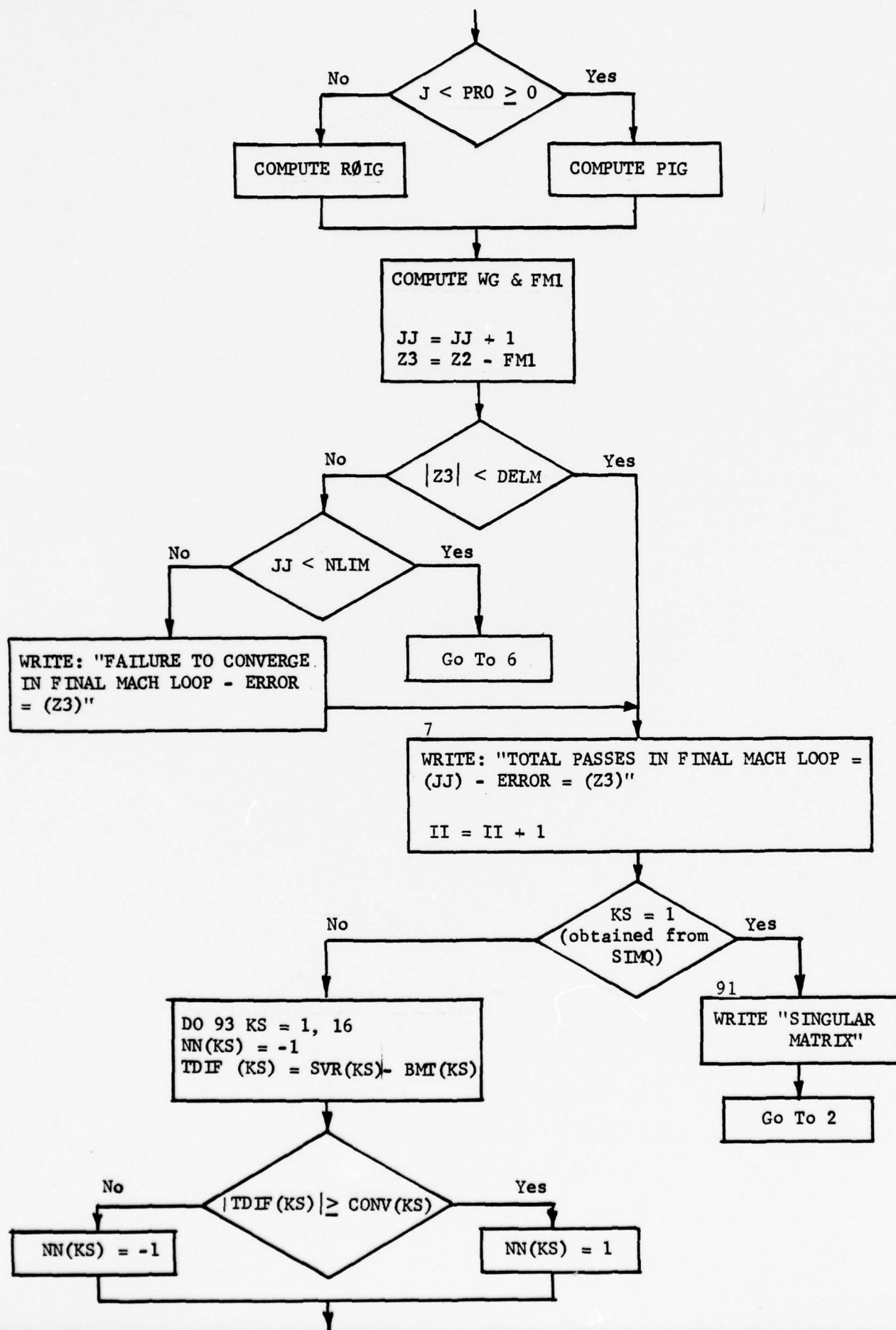


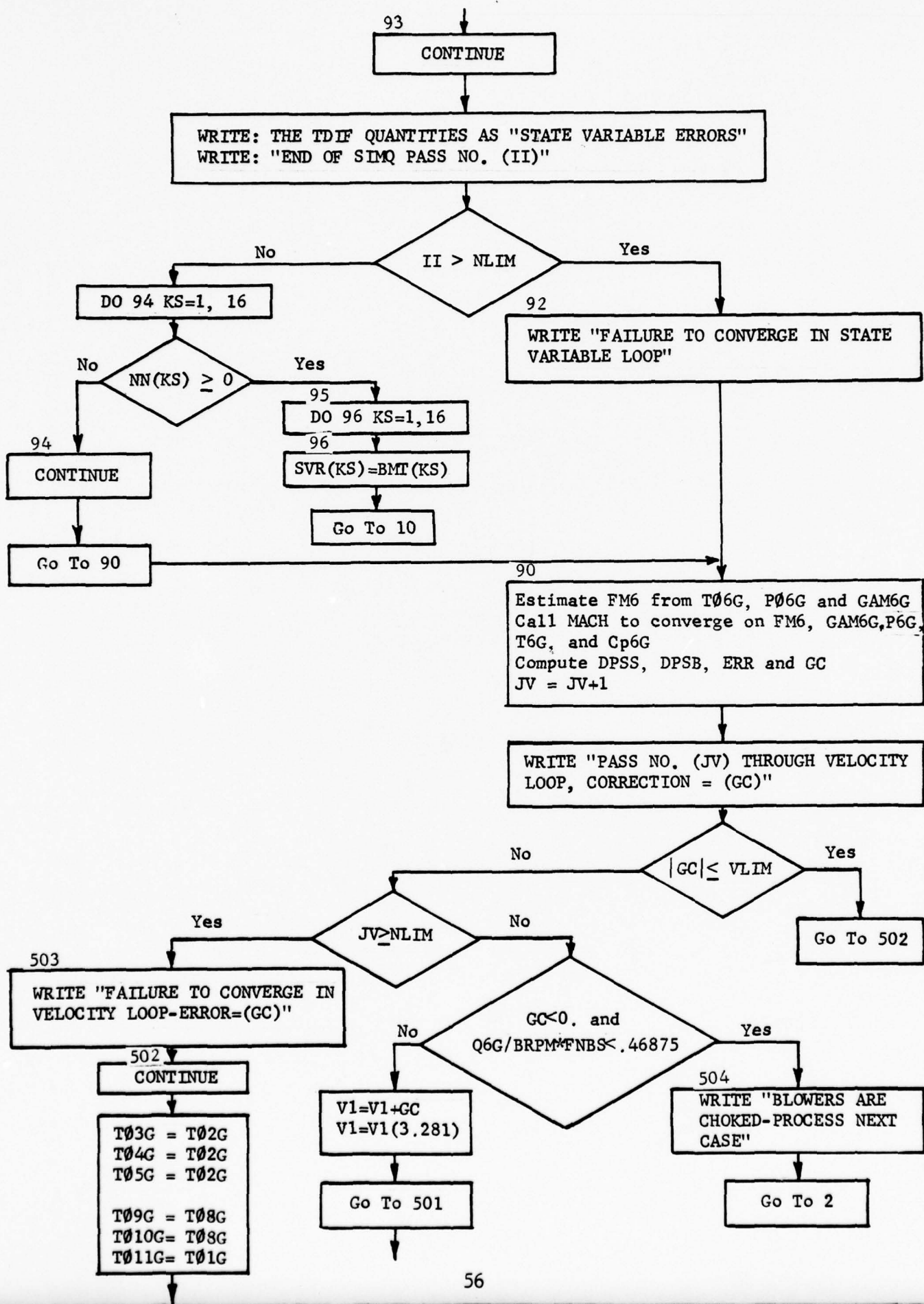














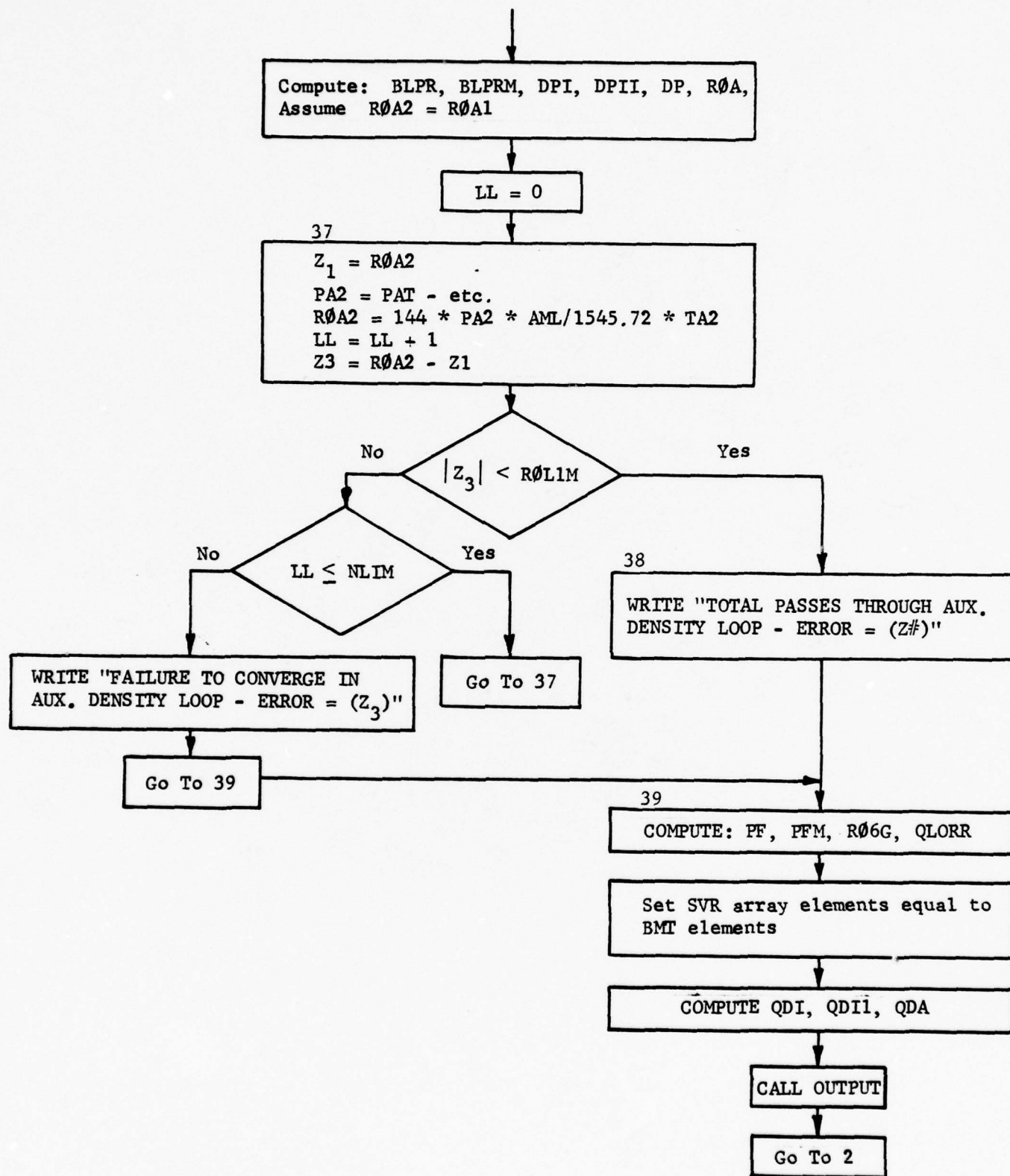


TABLE III

1.  $\frac{WG(CPIG + CP2G)(TO1G) + (-WG(CPIG + CP2G))(TO2G)}{2} = QS-.948(PLKW)(1./EFFL-1.)$
2.  $CGI(TO2G) - CGI(TO6G) + (WI(.5)(CP2 + CP4))(T2) + (-WI(.5)(CP2 + CP4))(T4) = 0$
3.  $(EPSI(CMINI)-CGI)(TO2G) + CGI(TO6G) - (EPSI(CMINI)(T2)) = 0$
4.  $\frac{-(PO7G/PO6G)GAM6G-1.}{ATAB(GAM6G)} (TO6G) + 1.(TO7G) = 0$
5.  $-CGII(TO1G) + CGII(TO8G) + (WII(.5)(CP2 + CP6))(T2) - (WII(.5)(CP2 + CP6))(T6) = 0$
6.  $CGII(TO1G) + (EPSII(CMINII)-CGII)(TO8G) - EPSII(CMINII)(T2) = 0$
7.  $-W3(.5)(CP1 + CP3)(T1) + W3(.5)(CP1 + CP3) - (CA(TA2)) = -CA(TA1)$
8.  $EPSA(CMIN)(T3) - (CA(TA2)) = (EPSA(CMIN)-CA)(TA1)$
9.  $W3(.5)(CP1 + CP2)(T1) - W3(.5)(CP1 + CP2)(T2) = -QP$
10.  $-WB(.5)(CP2 + CP3)(T2) + \{WI(.5)(CP4 + CP3) + WII(.5)(CP6 + CP3) + WM(.5)(CP16 + CP3) + WB(.5)(CP2 + CP3) + WV1(.5)(CP8 + CP3) + WV2(.5)(CP10 + CP3) + WE(.5)(CP18 + CP3) + WS(.5)(CP20 + CP3)\}(T3) - WI(.5)(CP4 + CP3)(T4) - WII(.5)(CP6 + CP3)(T6) - WV1(.5)(CP8 + CP3)(T8) - WV2(.5)(CP10 + CP3)(T10) - WM(.5)(CP16 + CP3)(T16) - WE(.5)(CP18 + CP3)(T18) - WS(.5)(CP20 + CP3)(T20) = 0$
11.  $WM(.5)(CP2 + CP14)(T2) - WM(.5)(CP2 + CP14)(T14) = -QCM$
12.  $WM(.5)(CP14 + CP16)(T14) - WM(.5)(CP14 + CP16)(T16) = -QM$
13.  $WV1(.5)(CP2 + CP8)(T2) - WV1(.5)(CP2 + CP8)(T8) = -QV1$
14.  $WV2(.5)(CP2 + CP10)(T2) - WV2(.5)(CP2 + CP10)(T10) = -QV2$
15.  $WE(.5)(CP2 + CP18)(T2) - WE(.5)(CP2 + CP18)(T18) = -QE$
16.  $WS(.5)(CP2 + CP20)(T2) - WS(.5)(CP2 + CP20)(T20) = -QS$
17.  $CGIII(TO7G) + WIII(.5)(CP7 + CP8)(T2) - CGIII(TO8G) - WIII(.5)(CP7 + CP8)(T7) = 0$
18.  $CGIII(TO8G) + (EPS3(CMIN3)-CGIII)(TO7G) - EPS3(CMIN3)(T7) = 0$

## Chapter V

### ANALYSIS OF OPTICAL RESONATORS WITH TILTED SPHERICAL MIRRORS

This study has employed closed-form analytical studies (of a two-dimensional approximation), extensions of previously existing computer codes, and newly prepared three-dimensional computer programs. This report will be concerned primarily with a summary of major aspects of the study and its conclusions; details have been furnished separately. The work has been coordinated with a MIRADCOM experimental investigation employing interferometry; the theoretical-computational and experimental results are in satisfactory agreement.

The development of theoretical and computational methods not only affords insight into observed trends, but provides a capability for determining expected optical quality properties of additional detailed designs without the need for an experimental study for each such design.

The investigations were primarily concerned with the effect, on an initially collimated beam, of one complete passage from convex to concave mirror, as indicated schematically in Figure 1. The two types of configurations, distinguished by the difference in relative signs of tilt angles of the two spherical mirrors, are referred to as "U-type" and "Z-type." The basic design equations, as given in Reference 1, do not distinguish between these two types of configurations. One of the purposes of the present study was to compare optical-quality properties of the two types. It turns out that the Z-type configuration is clearly to be preferred to the U-type configuration as regards output optical quality.



Fig. 1A. Schematic Drawing of "U-Type" Resonator.



Fig. 1B . Schematic Drawing of "Z-Type" Resonator.

### Two-Dimensional Approximation

By using a local wave front curvature approach in the two-dimensional approximation, it was possible to derive a closed form approximate expression for the optical path difference, here labelled  $z$ , as a function of lateral displacement  $y$ , and of other parameters of the resonator:

$$z = \frac{1}{R_2^3 \cos^3 \theta_2} \left[ - |R_1| \sin \theta_1 \pm R_2 \sin \theta_2 \right] y^3 .$$

The above expression is perhaps deceptively simple in appearance, since the value of  $\theta_2$  which appears in it must be determined from additional equations, which are given in Reference 1. The points to which attention are here drawn are:

(1) The  $z$ -dependence is of the form  $C_{03} y^3$ , i.e. of third power in transverse position  $y$ .

(2) The choice of signs in the numerator is such that the Z-type configuration is clearly better, as regards optical quality, than the U-type configuration.

(3) The dependence on mirror radii of curvature is, roughly speaking, of inverse-square type.

In addition to the closed-form analysis leading to the equation given above, two-dimensional numerical calculations were carried out, which tended to confirm the above conclusions.

The equation given above could be rewritten in the form

$$z_{cp} = C_{03} y^3$$



where  $Y$  is used to represent the maximum value of  $y$ , measured from center to edge, and the subscripts  $cp$  refer to the center-to-peak deviation. The optical quality is essentially determined by root-mean-square values of the optical-path deviations; these depend, of course, on the reference plane with respect to which they are measured. We will use  $z_{rms,nt}$  to refer to rms values with no tilt of the reference plane, i.e., the reference plane is chosen as strictly perpendicular to the output central ray. The actual optical properties will be determined by the rms deviations with respect to a reference plane whose tilt is optimized; the corresponding value of  $z$  will be labelled as  $z_{rms,opt}$ . It was found that in the two-dimensional approximation, the following equations apply:

$$z_{rms,nt} = 0.378 \ z_{cp},$$

$$z_{rms,opt} = 0.4 \ z_{rms,nt}.$$

Specific numerical predictions of the above two-dimensional equations are listed in Table I for a situation corresponding to an experimental study, for a range of values of convex-mirror tilt angles  $\theta_1$ . Three-dimensional predictions for the same cases will be given below for comparison.

Table I.

Two-Dimensional Approximate Predictions of Optical Path Differences in Microns, for a Z-Configuration Travelling Wave Resonator with  $R_1 = -290$  cm,  $R_2 = 675$  cm,  $Y = y_{\max} = 7.62$  cm, for Various Values of Convex Mirror Tilt Angle  $\theta_1$ .

The second column gives the center-to-edge values, the third column gives the rms OPD for an untilted reference plane, while the fourth column gives the rms OPD relative to an optimally-tilted reference plane.

$\theta_1$ (deg)	$z_{cp}$	$z_{rms,nt}$	$z_{rms,opt}$
10	0.393	0.149	0.059
20	0.855	0.323	0.129
30	1.481	0.560	0.224
45	3.168	1.198	0.479
50	4.165	1.574	0.630
55	5.614	2.122	0.849
60	7.866	2.973	1.189
70	19.233	7.270	2.908

### Three-Dimensional Calculations

The major portion of this study has been concerned with developing and applying three-dimensional ray-tracing computational methods.

A collimated beam is assumed to be incident on the convex mirror. Given  $x$  and  $y$  coordinates of an incident ray measured relative to the central ray, the computer program calculates the path of the ray through the system and determines (a) direction cosines after reflection from the concave mirror, measured in a coordinate system with the positive  $z$ -axis parallel to the central ray and (b) the optical path difference (OPD) between the ray considered and the central ray. The OPD's are of primary interest, and are calculated for a position close to the concave mirror. It was found necessary to utilize double precision arithmetic in order to obtain reliable values of OPD's.

Included in the input data are half-widths, in the  $x$  and  $y$  directions, of the desired output beam and the number of mesh points along  $x$  and  $y$  (usually  $9 \times 9$ ). Coordinates  $x$  and  $y$  of incident rays are obtained by dividing corresponding desired coordinates of output rays by magnifications  $M_x$  and  $M_y$ , which are computed by the program from input values of  $R_1$ ,  $R_2$ , and  $\theta_1$ . Unless otherwise specified, the program uses the values of mirror spacing  $L$  and of concave mirror tilt angle  $\theta_2$  which result in a collimated output beam, values of these parameters being determined by an initial portion of the program. The first page of computer output is a table of calculated OPD's over the specified mesh; the OPD's are given in microns, while mirror spacing and radii of curvature are in centimeters.

It was found that there is a good deal of order in the calculated OPD's as might be expected, and that their functional dependence on  $x$  and  $y$  can be rather well represented by a relatively small number of terms of

a Taylor's expansion. Of primary importance are terms  $C_{03} y^3$  and  $C_{21} x^2 y$ ; values of the coefficients  $C_{03}$  and  $C_{21}$  are not the same. The quadratic terms  $C_{20} x^2$  and  $C_{02} y^2$  can, of course, be important if the system is not properly adjusted. These terms have been included in the function fitting process in order to be able to investigate the effects of adjusting  $L$  and  $\theta_2$  to values slightly different from their ideal values. Also allowed for is a cross-term  $C_{22} x^2 y^2$  as well as fourth-order terms of the form  $C_{40} x^4$  and  $C_{04} y^4$ .

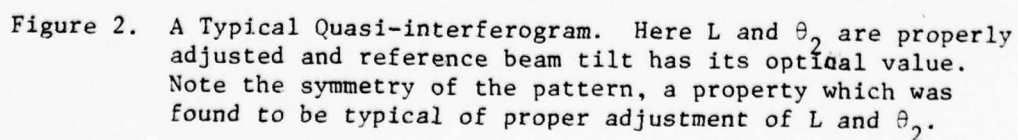
The computer program evaluates the series coefficients from the table of calculated OPD's and prints these. It also calculates and prints a table of residuals showing the difference between the directly calculated OPD's and values obtained from the truncated series expansion; these seem typically to be of the order of one percent or less of the OPD's themselves. The coefficient  $C_{\text{tilt}}$  corresponding to a reference plane defined by  $z = C_{\text{tilt}} y$ , which minimizes the rms OPD, is also determined and printed. Also a table is printed of the rms values of OPD for various values of reference beam tilt measured in units of the optimal value.

If  $L$  and/or  $\theta_2$  are set to values which are incremented slightly from their proper values there will be wave-front curvature in either or usually both the  $x$  and  $y$  directions, i.e.,  $C_{20}$  and/or  $C_{02}$  will differ appreciably from zero. Expected values of these coefficients can be derived analytically and compared with results of the function fitting process applied to the ray tracing OPD calculations. Agreement noted between analytically predicted and "function-fitting" calculated values is felt to be a confirmation of proper functioning of the computer program.

The primary experimental data regarding optical quality from tilted-spherical mirror resonator are in the form of interferograms. While

providing very precise and detailed information about the optical systems, interferograms do not immediately (without an intervening measurement and data-reduction process) lead to quantities predicted by the calculations. For the purpose of comparing experiment and calculations, it, therefore, seemed useful to convert the calculated OPD results into the form of computer simulated quasi-interferograms. For this purpose, the computer generates a fairly large (49 x 49) array of OPD's obtained by evaluation of the truncated series expansion at each of the array points. The array of numerical values is then converted to an array of alphabetic characters or blanks and used to generate a one-page printer plot whose general appearance simulates that of an interferogram. Successive characters of the alphabet correspond to incremental OPD's of one wavelength (0.6328 micron). The interspersing of blanks with letters of the alphabet has the result that (at least in the central portion of the plot) light areas are interspersed with dark areas, and hence, simulate an interferogram. An example of a computer generated quasi-interferogram is given in Figure 2.





The computer program will optionally produce multiple quasi-interferograms, corresponding to a specified set of reference beam tilts, from a single set of OPD calculations. The observed progression of shapes as tilt is systematically varied has proven interesting and useful since, of course, reference beam tilt can also be varied experimentally.

Inspection of quasi-interferograms leads to some interesting observations for a properly-aligned system (which was treated computationally prior to investigating effects of incremented values of  $L$  and  $\theta_2$ ):

(1) There is symmetry in  $x$ , as would be expected since the entire optical system is assumed to have such symmetry.

(2) For Z-type configurations, the pattern is symmetric in  $y$  to a fairly high degree of approximation (the OPD's are approximately anti-symmetric).

(3) For Z-type configurations there is a regular progression of shapes as reference beam tilt is increased from zero to its optimal value and beyond. Specifically, the pattern changes from a single central oval to a pair of ovals, symmetrically spaced about  $y = 0$ , which move further apart and are separated by an increasing number of fringes.

The properties just noted should be useful in experimental adjustment of  $L$  and  $\theta_2$ , since the symmetry in  $y$  seems to be a rather good "signature." Calculations made with values of  $L$  and/or  $\theta_2$  which are incremented from their ideal values produce quasi-interferograms which are quite noticeably lacking in the  $y$ -symmetry property.

A number of calculations were made for  $\theta_1 = 45^\circ$ , for various values of  $\Delta L$  and  $\Delta\theta_2$  (as well as reference beam tilts). One can reduce to zero the coefficient of either the  $x^2$  or  $y^2$  term by suitable choice of one of the increments, (i.e.,  $\Delta L$  or  $\Delta\theta_2$ ), when the other is specified. Reduction

to zero of the  $C_{20} x^2$  term shows up most clearly; one notes from the plot that there is very little OPD variation along  $x$  for  $y = 0$ . When the coefficient of  $y^2$  is reduced to zero, the corresponding quasi-interferogram is somewhat more involved, since there is still an appreciable amount of aberration present associated with other expansion terms. What is especially noticeable is that the  $y$ -symmetry is decidedly absent; this emphasizes usefulness of the  $y$ -symmetry property in making experimental adjustments. If one reverses the signs of both  $\Delta L$  and  $\Delta\theta_2$ , the  $y^2$  coefficient still vanishes, there is still a lack of  $y$ -symmetry, and the plot is essentially just the mirror image of the plot obtained without reversal of signs. This mirror image property applies for any pair of magnitudes of  $\Delta L$  and  $\Delta\theta_2$ . In the special case of zero magnitudes of both these increments, the mirror image of the pattern is simply (to a rather good approximation) identical with the pattern itself; that is to say, the  $y$ -symmetry property is characteristic of proper adjustment of  $L$  and  $\theta_2$ .

For cases where comparisons have been made, it appears that the three-dimensional ray tracing calculations predict optical quality parameters which are not greatly different from those obtained by the much simpler approach based on the two-dimensional approximation. Some specifics will be given for one case. For the mirror parameters associated with the experimental studies, three dimensional ray tracing calculations have been carried out for a range of values of  $\theta_1$ ; results are listed in Table II. These results may be directly compared with the two-dimensional predictions of the same case as given in Table I. The 3D predictions of the optimized rms OPD range from only some 25% to some 50% larger than the 2D predictions.

Table II.

Three-Dimensional Ray Tracing Predictions of Optical Path Differences, in Microns, for a Z-configuration Travelling Wave Resonator with  $R_1 = -290$  cm,  $R_2 = 675$  cm,  $x_{\max} = y_{\max} = 7.62$  cm, for Various Values of Convex Mirror Tilt Angle  $\theta_1$ .

The second column gives the center-to-edge values (taken along y for  $x = 0$ ); center-to-corner values are somewhat larger but are not listed here. The third column gives the rms OPD for an untilted reference plane, while the fourth column gives the rms OPD relative to an optimally-tilted reference plane.

$\theta_1$ (deg)	$z_{cp}$	$z_{rms,nt}$	$z_{rms,opt}$
10	0.393	0.230	0.091
20	0.855	0.496	0.194
30	1.481	0.848	0.330
45	3.171	1.764	0.678
50	4.171	2.287	0.876
55	5.626	3.031	1.157
60	7.892	4.159	1.582
70	19.450	9.529	3.667



## Summary

1. A closed form expression was derived and confirmed for optical path difference in a two-dimensional approximation as a function of various resonator parameters.
2. The closed form expression was confirmed by numerical calculations in both two and three dimensions.
3. It was found that the Z-type configuration is clearly to be preferred to the U-type configuration as regards optical quality.
4. For the two-dimensional case, expressions were derived for the root-mean-square optical path difference, which is the proper measure of optical quality degradation. It was found that the rms deviation is substantially less than the maximum deviation.
5. A computer program was prepared for three-dimensional ray tracing calculations of optical path differences.
6. The 3D computer program was checked in various ways, including comparison to separate 2D calculations, and comparison to analytical predictions for effects of varying  $L$  and  $\theta_2$  from their proper values.
7. The 3D program was extended to extract Taylor's series expansion coefficients for OPD's and to use these to generate large (49 x 49) arrays of OPD's for various values of reference beam tilt angle.
8. The program was arranged to plot quasi-interferograms from the large arrays of calculated OPD's.
9. Various effects were investigated by performing series of 3D computer runs.
10. For properly adjusted  $L$  and  $\theta_2$ , the quasi-interferograms were found to range from a central oval to a symmetrically arranged pair of ovals as the reference beam tilt is increased.



11. Improper adjustment of  $L$  was found to result in introduction of wave front curvature of the same sign in both  $x$  and  $y$  coordinates.

12. Improper adjustment of  $\theta_2$  was found to result in introduction of wave front curvature of opposite signs for  $x$  and  $y$  coordinates.

13. Reversal of sign of incremental values of  $L$  and  $\theta_2$  was found to result in inverting the quasi-interferogram along the  $y$  dimension.

14. Proper adjustment of  $L$  and  $\theta_2$  was found to lead to quasi-interferograms which are symmetric in  $y$  (as well as  $x$ ). The  $y$ -symmetry property seems to be a useful "signature" for use in experimental adjustments.

15. Numerical predictions were made for rms OPD variations for selected cases. It was found that the full 3D rms OPD's were typically some tens of percent larger than the 2D values.

#### REFERENCES

1. Charles Cason, R. W. Jones, and J. F. Perkins, "Optical Resonators with Tilted Spherical Mirrors," U. S. Army MIRADCOM Technical Report H-77-9, Sept. 1977. Also published in Optic Letters, 2, Page 145-147, June 1978.

## Chapter VI

### CONTRIBUTIONS TO TECHNICAL CONFERENCES

- Section 1 -- Gas Dynamic and Acoustic Management for Visible Wavelength Lasers by Cornelius C. Shih and Charles M. Cason
- Section 2 -- Investigation and Management of Acoustical Waves in Closed Cycle High Energy Pulsed Lasers by G. R. Karr, C. C. Shih, Charles Cason and A. H. Werkheiser
- Section 3 -- Non-Linear Wave Propagations in a Pulsed High Energy Gas Laser by C. C. Shih, G. R. Karr, and Charles Cason
- Section 4 -- Measurements of Fluid and Thermal Characteristics of Re-circulating Laser Gas Flows in a Closed Cycle Circulator for Pulsed Lasers by Cornelius C. Shih, Gerald R. Karr and Charles Cason
- Section 5 -- Fluid and Thermal Characteristics of Closed Cycle Flow Systems for High Power Lasers by G. R. Karr, C. C. Shih, C. M. Cason, and Vernon Ayre

## Section 1

Presented at SPIE Advances in Laser Technology 1978, Bellingham, Washington, March 1978.

### GAS DYNAMIC AND ACOUSTIC MANAGEMENT FOR VISIBLE WAVELENGTH LASERS

Cornelius C. Shih

The University of Alabama in Huntsville  
Huntsville, Alabama

and

Charles M. Cason

U.S. Army Missile Research and Development Command  
Redstone Arsenal, Alabama

#### Abstract

Criteria for fluid and thermal properties delineating the baseline flow homogeneity, such as those for  $AT/T$ ,  $AP/P$ ,  $\Delta\phi/\phi$ , and  $\Delta U/U$  will be established. These are based on medium-optical characteristics and requirements in terms of wavelength, pressure, and temperature of the gas medium associated with visible wavelength lasers. To meet these criteria, various methods for conditioning the baseline flow from the standpoint of gas dynamic and acoustic technologies will be presented and discussed. The merits of open and closed cycles for the baseline flow will be evaluated through consideration of gas utilization efficiency and component requirements. These criteria become acoustic dominated for pulsed lasers. The pulse repetition frequency required for a given laser defines the clearing time allowed to restore the original baseline flow. A parallel consideration becomes necessary to account for the pulse input perturbation. Solutions to acoustic management problems must be obtained by considering all sources of reflection, acoustic characteristics of open and closed cycles in terms of wave propagation, attenuation, and dissipation.

#### Introduction

In recent years, visible wavelength lasers of  $KrF$ ,  $XeF$ , and  $HgCl$  have wide-spread interest in the field of high energy laser technology because of the potential applications. These visible lasers with wavelengths ranging from 0.25 to one micron are generally known to attain lasing conditions suitably at the temperatures of 500°K - 5000°K. The concept of repetitively pulsed energy input through the use of an electron-beam or self-sustained discharge into the laser cavity has been shown to be an efficient and compact means of achieving high power levels in Argon and Helium at one to five atmospheric pressures. In such a system, the e-beam, through secondaries, supplies direct pumping energy to Argon and also produces a plasma in the laser cavity. Across the plasma, a sustainer voltage is applied at an adjusted field strength to excite the laser states with optimum pumping. If the lasing pulse duration is approximately equal to the relaxation time of the lower lasing state, the optimum lasing output is achieved. On the other hand, shorter pulses will cause a premature self-termination of lasing process, and longer pulses will result in gas heating and reduction of the lower state capacity. The pulse duration is considered to be approximately one  $\mu$  second for the gas composition and temperature of interest.

In the operation of electrically pulsed lasers, the abrupt deposition of energy in the laser media causes the development of pressure and temperature variations. The resulting pressure and temperature gradients are responsible for producing acoustical perturbations. Optical beam quality is known to be degraded by acoustically produced density fluctuations as noted by previous investigations particularly for CO<sub>2</sub> lasers (1), (2), (3), (4), (5). To avoid these defects, the heating of laser gases must be accommodated by both applying a pulsed duty cycle of sufficient duration and imposing a flow of the gases through the cavity. Therefore, efficient operation of the visible wavelength pulsed lasers requires serious attention to gas dynamic and acoustic management of the laser media in the flow systems. The flow systems under consideration are either open (blow-down) or closed cycle (recirculator) type. The power input for these lasers of interest is limited practically at about 100 Joules per liter of cavity volume under various operational constraints, while the length of laser cavity along the optical axis is chosen at 100 cm for present study.

This paper is intended to focus attention on technical issues pertinent to the gas dynamic and acoustic management for the flow systems of the high power visible wavelength laser with repetitively pulsed modes of operation under the above mentioned constraints on the laser parameters. Specifically, issues to be discussed are as follows: medium homogeneity criteria; methodology of gas dynamic and acoustic management of the baseline flow; merits of open and closed cycle flow systems.

In this study, the energy deposition in the laser gas cavity is assumed to be for the duration of one  $\mu$  second as the pumping boundary condition representative of desirable e-beam, e-beam plus discharge, or externally initiated TEA approaches. However, problems of electric pumping, arcing limits, and kinetic details for specific electric discharge laser gas systems are not considered in the paper.



### Baseline Flow Homogeneity Criteria

Fluid and thermal properties governing the baseline flow homogeneity of high power lasers are closely associated with the radiation intensity ratio in defining the beam quality. The intensity ratio,  $I/I_0$  in the far field where  $I_0$  refers to the diffraction limited far field central spot intensity and  $I$  denotes the reduced intensity due to induced aberrations. For small  $r$  and down fluctuation, it is directly related to the square of the rms fractional density fluctuation,  $\Delta\rho/\rho$ . Systematic, large-scale ordered variations in the density,  $\rho$ , cause the optical pathlengths along the ray paths to vary, while smooth ordered  $\rho$  variations produced in the flow that causes a spatial tilt plane error in the phase front which is a fundamental loss. Linear plane errors in the spatial phase,  $\phi$ , can be corrected by careful resonator mirror alignment to require the optical pathlengths along the rays to be the same.

Relatively small randomized density fluctuations in the flow field can cause spatial phase,  $\phi$ , fluctuations that have no simple temporal and spatial order. A qualitative estimate of the allowable  $(\Delta\rho/\rho)_{\text{rms}}$  can be made for small phase aberrations by use of the Strehl criterion,

$$I/I_0 = \exp(-\phi_{\text{rms}}^2) \approx 1 - \phi_{\text{rms}}^2 \quad (1)$$

at the point that errors become significant because higher order terms are neglected in Eq. 1,  $I/I_0 < 0.8$ . Specifying this optimizational point requires  $1 - \phi_{\text{rms}}^2 \geq 0.8$ . The spatial phase front criteria becomes  $\phi \leq .071\lambda_{\text{rms}}$  where  $\lambda$  is the optical wavelength. Using this criteria to determine the maximum allowable rms pathlength gives a useful medium quality parameter in terms of gas density variation:

$$L(\Delta\rho/\rho)_{\text{rms}} \leq .071\lambda_{\text{rms}} \rho_{\text{ref}}/\alpha\beta \quad (2)$$

where  $L$  is the optical pathlength, for resonators with large out-coupling,  $\frac{\partial\phi}{\partial\text{ref.}} = n-1$  where  $n$  is the index of refraction,  $\beta$  the Gladstone-Dale constant,  $\rho$  the gas density,  $\rho_{\text{ref}}$  the density at STD conditions. Using the given requirement for the medium quality for 2 atm typical visible laser mixtures gives  $L(\Delta\rho/\rho)_{\text{rms}}$  to be  $3.2 \times 10^{-3}\text{cm}$ ,  $1.5 \times 10^{-3}\text{cm}$  and  $1.2 \times 10^{-3}\text{cm}$  of KrF, XeF, and HgCl, respectively in Argon at 2 atm. Values of  $(\Delta\rho/\rho)_{\text{rms}}$  for most E-beam pumped  $\Lambda_r$  mixtures are therefore approximately  $10^{-6}$  and for TEA discharges in He  $(\Delta\rho/\rho)_{\text{rms}}$  is approximately  $10^{-4}$  for  $L = 100\text{ cm}$ .

Reducing the scale of the density fluctuations further reaches a point wherein the far field intensity is degraded by scattering<sup>(6), (7)</sup> a portion of the optical beam from the resonator. This portion of the output laser energy will appear as a very broad flattened background in the far field to be added to the proportionally reduced Fraunhofer pattern.

The approximations used to determine the allowed  $(\Delta\rho/\rho)_{\text{rms}}$  for specified values of  $L$  provide little beyond a qualitative feel for high gain systems having large output coupling. Real cases may impose more stringent  $(\Delta\rho/\rho)_{\text{rms}}$  requirements. Numerical calculations to correctly determine the phase-perturbed cavity properties would be expensive and should be very carefully planned<sup>(6)</sup>. However, the very important systems advantage of the Helium diluent over Argon presents a flow medium quality of  $\Delta\rho/\rho = 10^{-6}$  may be obtainable for 100 cm He mixtures.

The medium homogeneity is expressed in acoustic terms for the two laser gases, Helium and Argon at two ATM under the normal laser conditions. The  $(\Delta\rho/\rho)_{\text{rms}}$  for the two gases are expressed graphically in terms of the driving sound pressure level in Figure 1. It shows that acoustical energy in Helium will produce a lower  $(\Delta\rho/\rho)_{\text{rms}}$  than the same level in Argon laser.

The criteria established in terms of  $\Delta\rho/\rho$  for various visible wavelength lasers (VWL) are based on the beam quality requirements, and they are considerably restrictive, about two orders of magnitude higher than those applied to the pulsed chemical lasers. This unfavorable situation is amplified by the fact that the flow Mach numbers of about 0.5 for the VWL are noted to be larger than for most other pulsed EDL. This study considers the issues concerning the sources of medium inhomogeneity in the baseline flow due to the pulsing as well as the gas dynamic and acoustic management of the perturbations has been given in this study.

### Gas-Dynamic and Acoustic Phenomena in the Pulsed Laser Operation

The gas density response to rapid volumetric heating takes place after lasing because the acoustic time constant is relatively long, 30 to 100  $\mu\text{sec}$ .



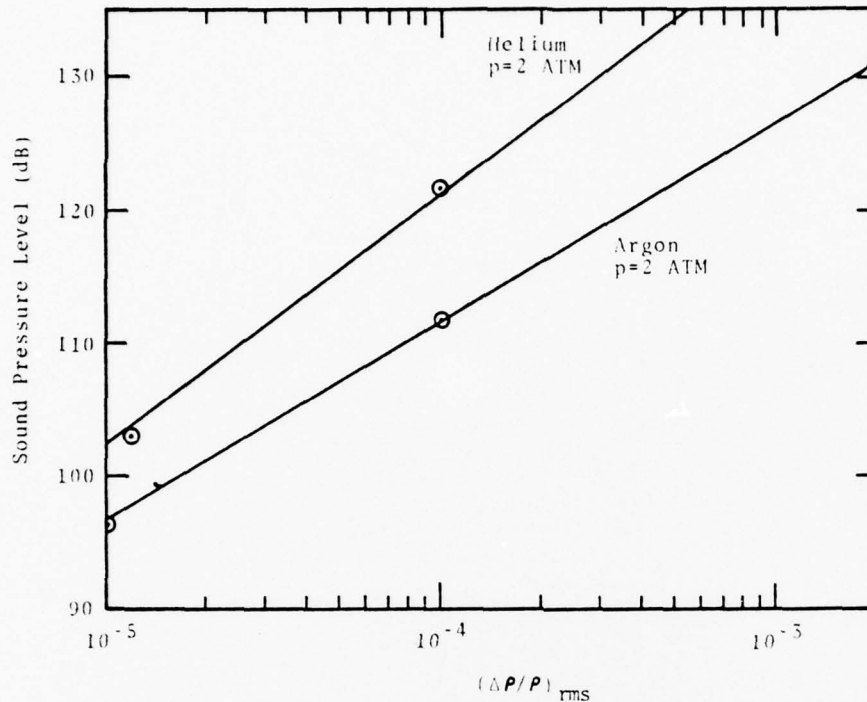


Fig. 1: Sound Pressure Level Versus  $(\Delta p/p)_{rms}$  for Helium and Argon at 2 atm.

Although it has been determined that this acoustically significant temperature rise occurs on a relatively long time comparing with the pulse duration of about 10 sec, but it is short for significant changes in the liter size flow system at the cavity. Thus, the assumption of constant volume heating of the gas in the cavity is reasonably justified for the gas dynamic analysis of the flow systems under the pulsed operation. The temperature rise coupled with pressure surge in the slug of laser gas in the cavity generates the formation of shock waves and expansion waves which lead to the issuance of an interface or so-called contact surface between them. Propagations and reflections of these pressure waves complicated by the existence of the interface separating the heated gas from the cold in the flow system contribute the main source of thermo-acoustical problems in subsequent pulses. Qualitative descriptions of these thermo-acoustic phenomena are presented graphically in space vs. time plane in Figure 2 and in space vs. thermodynamic properties for various time frames in Figure 3. These graphical presentations were developed from numerical results of computer modeling of the laser gas flow system under pulsed operation based on the method of characteristics. The computer code devises a simultaneous approximate solution of the coupled state, continuity, momentum and energy equations including the effect of friction for the time-dependent one-dimensional flow of the pulsed laser gas system centered around the laser cavity<sup>(8)</sup>.

Sources of random medium inhomogeneity accumulatively contributes additive rms elements that degrades the beam quality. It is expressed in terms of  $\Delta\rho/\rho$  as follows:

$$\text{Total } \left( \frac{\Delta\rho}{\rho} \right)_{rms} = \left[ \left( \frac{\Delta\rho}{\rho} \right)_{rms}^2 \text{ Thermodynamics} + \left( \frac{\Delta\rho}{\rho} \right)_{rms}^2 \text{ Turbulence} + \left( \frac{\Delta\rho}{\rho} \right)_{rms}^2 \text{ Acoustics} \right]^{1/2} \quad (3)$$

where

$$\left( \frac{\Delta\rho}{\rho} \right)_{rms}^2 \text{ Thermodynamics} \approx \left( \frac{\Delta T}{T} \right)_{rms}^2 \quad \text{for temperature fluctuations in boundary layers, interfaces and other flow components.} \quad (4)$$

$$\left( \frac{\Delta\rho}{\rho} \right)_{rms}^2 \text{ Turbulence} \approx \frac{1}{2} M_\infty^2 \left( \frac{\Delta u}{u_\infty} \right)_{rms}^2 \quad \text{for free stream turbulence} \quad (5)$$

$$\approx C_f M_\infty^2 \frac{\delta^*}{2} \quad \text{for boundary layer turbulence} \quad (6)$$

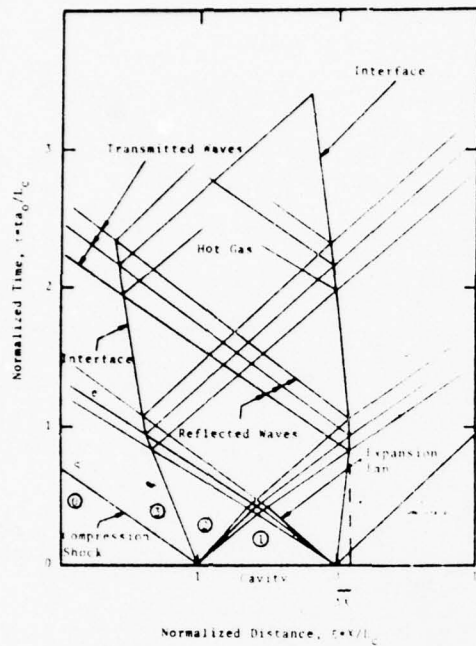


Fig. 2: Wave Propagation and Interaction Due to Pulsed Energy Input

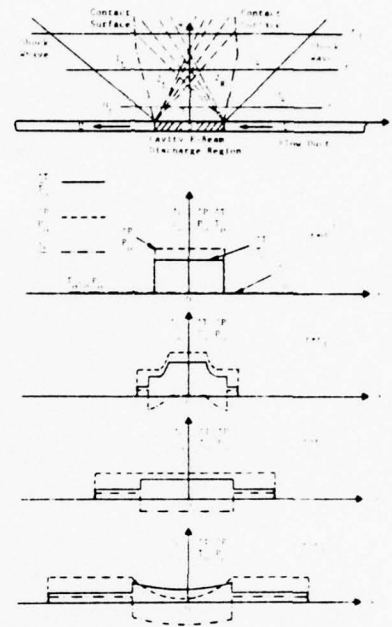


Fig. 3: Thermodynamic Property Variations Versus Space for Various Time Frames

- $\delta^*$ : boundary layer displacement thickness  
 $l$ : boundary layer characteristic length  
 $C_f$ : skin-friction coefficient  
 $u_m$ : average flow velocity in the cavity  
 $M_m$ : Mach number in the cavity  
 $\Delta u_m$ : rms longitudinal turbulent velocity fluctuation

$$\left( \frac{\Delta \rho}{\rho} \right)_{\text{rms}} \sim \frac{1}{\gamma} \left( \frac{\Delta p}{p} \right) \frac{\gamma + 1}{2 + M_s^2(\gamma + 1)} \quad \text{for shock waves} \quad (7)$$

$$= \frac{1}{\gamma} \left( \frac{\Delta p}{p} \right) \quad \text{for acoustic waves where } M_s = 1 \quad (8)$$

In order to attain the beam quality required, the total  $(\Delta \rho/\rho)_{\text{rms}}$  must meet the criteria of  $10^{-5}$  for KrF and XeF in Argon and  $10^{-4}$  for TEA discharges in Helium and  $\text{HgCl}$  in Argon, respectively. Technical challenges are evident in the methodology for gas dynamic and acoustic management of these medium homogeneity problems.

From the quantitative viewpoint of excessive energies remaining in the flow system to be managed, they can be represented by the following equation derived from the energy balance and thermodynamic relationships of the flow system:

$$A_c = [1 + R_c] - (1 + R_c)^{1/\gamma} \quad : \text{Acoustic Energy Ratio} \quad (9)$$

where

$$A_c = \frac{E_d}{E_0}, \quad R_c = \frac{E_{in} - E_L}{E_0} \quad : \text{Remaining Energy Ratio}$$

# GAS DYNAMIC AND ACOUSTIC MANAGEMENT FOR VISIBLE WAVELENGTH LASERS

$E_a$ : Acoustic energy to be managed

$E_L$ : Lasing energy output

$E_0$ : Energy of the baseline flow,  $E_0 = C_v T_0$

$\gamma$ : Specific heat ratio

$E_{in}$ : Pulsed energy input

The above relationship is graphically presented in Figure 4 for various  $\gamma$ . For the VWL of interest, the above Equation 4 is modified in dimensional form with the given  $\gamma$  of 1.67 and presented in Figure 5 with energy input in Joule/litre versus acoustic energy efficiency,  $E_a/E_{in}$  in percent for a range of energy input peculiar to the VWL<sup>(9)</sup>.

Magnitudes of the remaining energies which must be managed are known to be about 90% of the total energy input while about 10% of the energy becomes lased energy output from the cavity. Figure 5 shows that the acoustic energy is about 40% of the input energy. The remaining is the thermal energy which must be removed by heat exchangers.

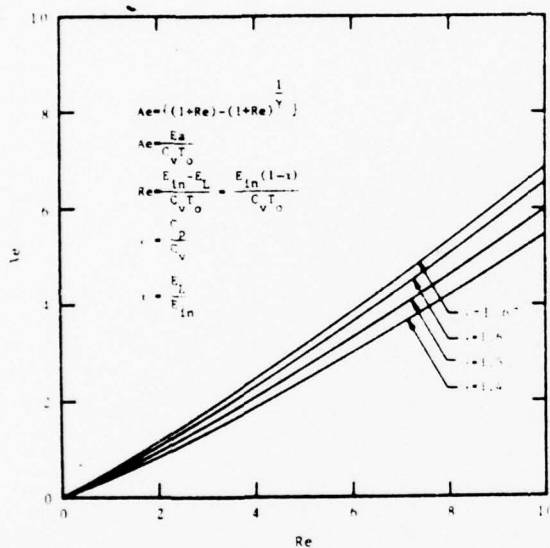


Fig. 4: Acoustic Energy Ratio Versus Remaining Energy Ratio for Various Specific Heat Ratios

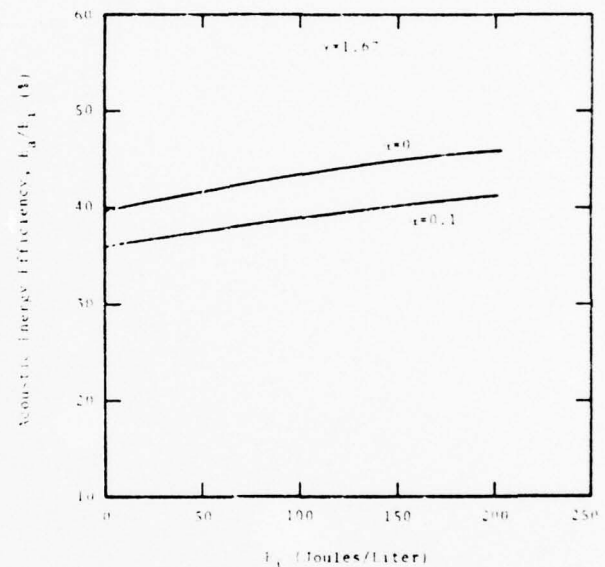


Fig. 5: Acoustic Energy Efficiency Versus Input Energy for VWL Gases

## Methodology of Gas Dynamics and Acoustic Management

Since the main sources of inhomogeneity are originated from the turbulence, temperature fluctuation, and pressure waves, contribution of respective solution approaches to various sources will be given as follows:

### Turbulence

Effects of free stream turbulence on  $\Delta\phi/\phi$  may be approximated by Equation 5:

$$\frac{\Delta\phi}{\phi} \approx \frac{1}{2} M_\infty^2 \left( \frac{\Delta u}{u_\infty} \right)_{rms}^2$$

The velocity fluctuation,  $\left( \frac{\Delta u}{u_\infty} \right)_{rms}$ , can be considerably reduced by suppressing turbulence upstream of the laser cavity. The technique to suppress the turbulence has been well developed and proven effective particularly in the wind tunnel practice. Use of damping screens suggested by Dryden<sup>(10)</sup> has been accepted as an effective method of turbulence suppression. Without application of any turbulence management system,

velocity fluctuations in a closed cycle circulator could be at least 10% at a Mach number around 0.5. With the use of properly designed contracting entrance to the cavity, and correctly sized screen packs, a sophisticated turbulence management system could suppress the turbulence down to the level below 0.1%. For  $M_\infty = 0.5$ ,  $\Delta\rho/\rho$  can be lowered to  $0.125 \times 10^{-5}$  with some moderate effort in this problem area.

Another source of turbulence exists in the boundary layers on the mirrors, their protective windows and cavity walls. Since the Reynolds number of the flow in the cavity region is determined to be above  $10^7$ , using  $M_\infty = 0.5$ , the boundary layer is definitely turbulent. Numerous experiments on turbulent boundary layers have confirmed that density fluctuations caused by boundary layer turbulence or eddies are larger than those due to freestream turbulence. A simplified expression of the relationship is given by Equation 6:

$$\frac{\Delta\rho}{\rho} \approx C_f M_\infty^2 \frac{\delta^*}{\ell}$$

Since  $C_f \delta^* = f(N_{RX}, X)$  where  $N_{RX}$  denotes the Reynolds number along the boundary layer,  $N_{RX} = \frac{UX}{\nu}$ ,  $X$  the space coordinate along the flow direction. A coarse estimate of  $\Delta\rho/\rho$  based on the value of  $C_f$  from Schlichting<sup>(11)</sup> for  $M_\infty = 0.5$  and  $N_{RX} = 10^7$  becomes

$$\frac{\Delta\rho}{\rho} \approx 0.5 \times 10^{-5} \frac{X}{\ell} \quad (10)$$

Equation 10 indicates that if the distance  $X$  from the virtual origin of the boundary layer is less than twice the boundary layer characteristic length which is comparable to the layer thickness, the fractional density fluctuation can be kept under control even for Argon flows. In practice, this can be accomplished by careful design of the cavity entrance or the application of boundary bleed along the cavity walls.

#### Temperature Fluctuations

The temperature rise in the heated slug of gas in the laser cavity after the pulsed energy input is expected to be about 30% of the original temperature for 100 Joules per liter of Ei and about 50% for Ei = 200 Joules per litre. Since the temperature of the baseline flow,  $T_0$ , is expected to be about 300°K, the thermal energy added into the slug of gas does not exceed 200 Joules per litre. This amount of heat in the baseline flow even at  $M_\infty = 0.5$  is easily manageable with efficient light weight heat exchangers.

As for the temperature fluctuations in the boundary layers at the mirrors, their protective windows, and the cavity walls, a preliminary study shows that the temperature at the boundary surface could rise not more than 10% for the boundary layer flow previously defined if  $\Delta\rho/\rho$  is to be limited under  $10^{-5}$ . Again cooling the boundary surfaces can be accomplished with the existing means. Detailed analysis of boundary layers should be deferred unless found necessary from the experimental measurements. The removal of input energy is a problem for the closed cycle type but is no concern for the open cycle flow system.

#### Pressure Waves

Pressure waves generated due to the pulsed energy input at the cavity in the flow system include shock waves and expansion waves. Realizing that propagation, reflection, transmission, and attenuation of these waves must be treated at least with nonlinear acoustic theory for the energy input range of 100 to 300 Joules per litre<sup>(9)</sup>; the concept and materials for the attenuator design should be based on the nonlinear acoustic consideration rather than the available linear acoustic theory and data.

First  $\Delta\rho/\rho$  due to the shock wave is represented with the following equation for  $\gamma = 1.67$ , a typical diluent gas, and  $M_s = 1.15$  for Ei = 200 Joules per liter and  $\Delta\rho/\rho = 0.403$ :

$$\frac{\Delta\rho}{\rho} = \frac{2(M_s^2 - 1)}{2 + M_s^2(\gamma - 1)} \quad (11)$$

Thus  $\frac{\Delta\rho}{\rho}$  becomes 0.224 and obviously requires attenuation of a strong measure.

On the other hand,  $\Delta\rho/\rho$  for acoustic waves under the isentropic process must be



$$\frac{\Delta P}{P} < k \frac{\Delta \rho}{\rho} \quad \text{required.}$$

Thus  $\frac{\Delta P}{P}$  must be less than  $1.67 \times 10^{-5}$  in order that the medium homogeneity is acceptable.

Under these stringent requirements for acoustic management, an effort is currently in progress at the University of Alabama in Huntsville to develop reactive attenuators such as a muffler with exponential horns as shown in Figure 6. Attenuation characteristics of the muffler is presented in Figure 7 for frequency versus attenuated dB. It shows that this particular type of muffler design will be effective in the frequency range up to 1 KHz and most effective in the 200 ~ 500 Hz.

There are many other reactive attenuators and sound absorbing materials for pressure damping or attenuation as reported in numerous literatures (12), (13), (14), (15), (16), and (17), however it is important that the attenuation characteristics with respect to the wave frequency must be carefully matched with the pressure waves generated in the laser flow systems so that the attenuation will be effective.

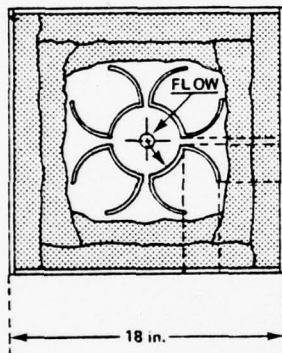


Fig. 6: Reactive Attenuator (Muffler)

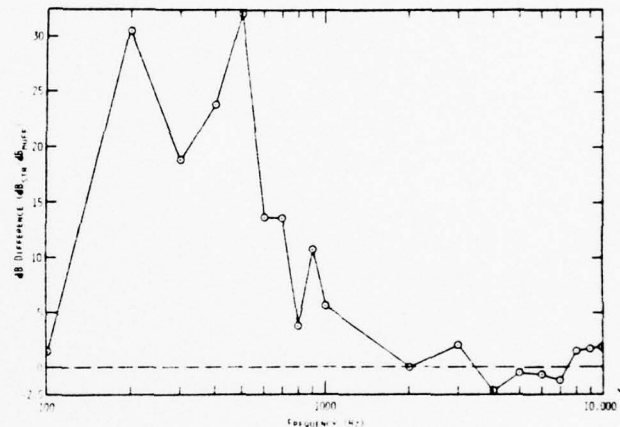


Fig. 7: Attenuation Characteristics in dB Versus Frequency of the Muffler

#### Consideration of Open Cycle and Closed Cycle Flow Systems

For delivering the laser gas suitably conditioned to meet homogeneity criteria at the cavity, a necessary flow system could be the open cycle or the closed cycle type. Choice of a system depends on various factors such as size and weight limitations, sources of gas supply, capabilities of gas dynamic and acoustic management, lasing energy output, and pulse rate restriction.

High energy laser technology has gained considerable advances in terms of experience, knowledge, design, and fabrication so far in the open cycle flow system for pulsed lasers through numerous projects such as ABEL, Humdinger, CCEBL, etc.; however, the closed cycle flow system or circulator has not been applied to high power pulse lasers extensively to the authors' knowledge, except the one being developed by the Army and being tested currently at Rocketdyne. Technical illustration and general view of the Army closed cycle gas recirculator are presented in Figures 8 and 9.

Comparative evaluation of the two systems is rather premature at this time due to its lack of sufficient data for analytical comparison; however, some of the significant comparative features of the two systems are noteworthy for system development considerations.

#### Open Cycle Flow System

- No heat exchanger is required at downstream side of the cavity since the heated gas will be blown down into the ambient.
- In the acoustic management, aside from proper application of resistive and reactive attenuators around the cavity, serious attention be given to the possible wave reflection of nonlinear nature at the system exit, which may be a serious management problem.
- The weight and size of the total system including the gas supply may be less flexible for optimization.
- The duration of operation may be limited by the size of gas supply.
- The potential for higher repetitive pulse rate exists.
- Reconditioning or repurification of the gas is not required.



## Closed Cycle Flow System

- a) Economy in gas consumption and supply is evident.
- b) Gas dynamic management of the laser gas in terms of reconditioning to desirable temperature, pressure, velocity, and turbulence is a challenging task requiring additional heat exchangers.
- c) Repurification of the gas may be required in some system depending on the rate of degradation and thermal environment.
- d) Acoustic management of the pressure waves is as difficult as that of the open cycle type, but it lacks the concern for the wave reflection from the exit.
- e) Optimization of the system weight and size is more promising.
- f) The pulse rate may be less flexible for increase.

## ARMY CLOSED CYCLE GAS RECIRCULATOR

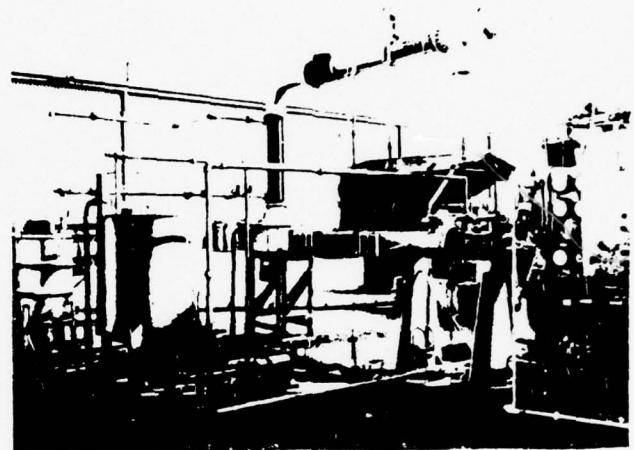
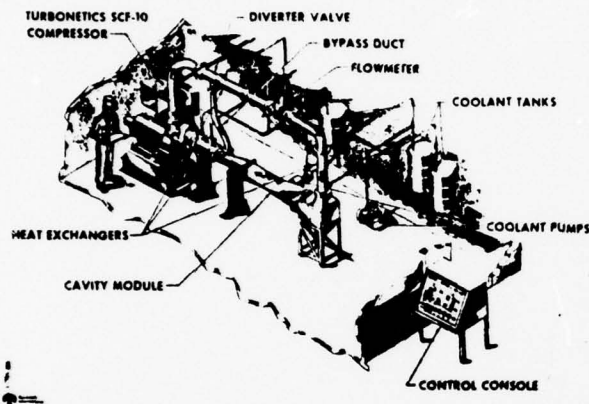


Fig. 8 and 9: Technical Illustration and General View

## References

1. Pugh, E. R.; Wallace, J.; Jacob, J. H.; Northam, D. B.; and Daugherty, J. D.: "Optical Quality of Pulsed Electron-Beam Sustained Lasers." *Appl. Optics*, Vol. 13, 1974, p. 251.
2. McAllister, G. L.; Draggoo, V. G.; and Eguchi, R. G.: "Acoustical Wave Effects on the Beam Quality of a High Energy CO<sub>2</sub> Electric Discharge Laser." *Appl. Optics*, Vol. 14, 1975, p. 1290.
3. Culick, F. E. C.; Shen, P. I.; and Griffins, W. S.: "Acoustical Waves Formed in an Electric Discharge Co Laser Cavity." *AIAA Paper No. 75-851*, 1975.
4. Kast, S. and Cason, C.: "Performance Comparison of Pulsed Discharge and E-Beam Controlled CO<sub>2</sub> Lasers." *J. Appl. Phys.*, Vol. 44, 1973, p. 1631.
5. Basov, N. G.; Danilychev, V. A.; et al.: "Maximum Output Energy of an Electron-Beam-Controlled CO<sub>2</sub> Laser." *Sov. J. Quantum Electronics*, Vol. 4, 1975, p. 1414.
6. Holmes, D. A. and Avizonis, P. V.: "Approximate Optical Systems Model." *Appl. Opt.*, Vol. 15, No. 4, pp. 1075-1082, 1976.
7. Siegman, A. E.: "Effects of Small-Scale Phase Perturbations on Laser Oscillator Beam Quality." *IEEE J. Quantum Electron.*, Vol. QE-13, No. 5, pp. 354-357, 1977.
8. Shih, C. C. and Karr, G. R.: "Investigation of Transient Flow and Heating Problems Characteristic of High Energy Laser Gas Circulation Systems." *UAH Research Report No. 199 (H-CR-77-9)*, March, 1977.
9. Cason, C. and Horton, T. E.: "Thermal-Acoustical Phenomena in Pulsed High Energy Lasers." *ASME (78-HT-61)*, to be presented in May, 1978, at 2nd. AIAA/ASME Thermophysics and Heat Transfer Conference.
10. Dryden, H. L. and Schubauer, G. B.: "The Use of Damping Screens for the Reduction of Wind-Tunnel Turbulence." *J. Aero. Sciences*, pp. 221, Vol. 14, No. 4, April, 1947.
11. Schlichting, H.: *Boundary Layer Theory*, McGraw-Hill Co., 1968.
12. Kesselring, R. C. and Nestlerode, J. A.: "Pressure Damping for Pulsed Electric Discharge Laser." *Final Report, AMRL-TR-75-170*, Air Force Weapons Lab., Kirtland, AFB, New Mexico, July, 1975.
13. Horton, T. E., and Wolfe, K. E.: "Acoustical Problems in High Energy E-Beam Lasers," pp. 963-975, *Advances in Eng. Sciences*, Vol. 3, NASA CP-2001, Nov., 1976.
14. McMillion, R. L. and Nestlerode, J. A.: "Design Criterion for Acoustic Absorbers," *8th JANNAF Combustion Meeting* CPIA Publication, Nov., 1971.
15. Ingard, U. and Bolt, R. H.: "Absorption Characteristics of Acoustic Material with Perforated Facings," *J. Acoust. Soc. Amer.* 23, 5, pp. 533-540, Sept., 1951.
16. Rice, E. J.: "Propagation of Waves in an Acoustically Lined Duct with a Mean Flow," *NASA SP 207*, p. 345.
17. Mechel, F. and Schilz, W.: "Research on Sound Propagation in Sound-Absorbent Ducts with Superimposed Air Streams." *Tech. Report AMRL-TDR-62-140 (I-IV)*, Dec., 1962, Air Force Systems Command, Wright-Patterson AFB, Ohio.

Section 2  
Presented at International Symposium on Nonlinear Acoustics, Paris, France, July 3-6, 1978

INVESTIGATION AND MANAGEMENT OF ACOUSTICAL WAVES IN CLOSED CYCLE HIGH  
ENERGY PULSED LASERS

G. R. Karr and C. C. Shih  
The University of Alabama in Huntsville  
Huntsville, Alabama 35807

and

Charles Cason and A. H. Werkheiser  
U. S. Army Missile Research and Development Command  
Redstone Arsenal, Alabama 35809

Abstract

To investigate the acoustic problems in high energy, closed cycle, pulsed lasers, a closed cycle system was fabricated and attached to an existing E-beam controlled single pulse laser system. Electrical energy was input to one atm. flowing gas mixture typical of that required by CO<sub>2</sub> and excimer lasers. A frequency power spectrum of the produced acoustic pulse was measured and compared with the frequency power spectrum of acoustic energy transmitted and reflected by the muffler. The results showed the muffler attenuated the input wave nearly 40 db at near 500 Hz and 12 db at 5000 Hz.

Resumé

En vue d'étudier les problèmes acoustiques dans les lasers pulsés à haute énergie opérant en cycle fermé, un système à cycle fermé a été construit et rattaché à un laser opérant en pulse unique et contrôlé par un faisceau électronique. L'énergie électrique a été appliquée à un flow de mélange gazeux typique de celui exigé par les lasers CO<sub>2</sub> et excimer. Le spectre de puissance de l'impulsion acoustique produite a été mesuré et comparé avec le spectre de puissance de l'énergie acoustique transmise et réfléchi par le déflecteur. Les résultats montrent que le déflecteur atténue l'onde d'entrée par près de 40 db autour de 500 Hz et par près de 12 db autour de 5000 Hz.

## Introduction

The energy input into the cavity of a pulsed high energy gas laser causes shock waves and expansion waves which propagate away from the cavity and interact with system components.<sup>1,2,3</sup> This acoustical energy, if unmanaged, will interact with gas in the cavity, thereby seriously degrading the output laser beam quality. The work reported here describes experiments which identify the nature of the acoustic environment and the effectiveness of acoustic control devices in managing acoustic waves.

The sequence of operation of a pulsed high energy gas laser consists of (1) the laser gas media flows into the cavity region; (2) energy is deposited in the gas at a magnitude of  $10^2 - 10^3$  J/l in a total time of magnitude  $10^{-6}$  s; (3) shock waves and expansion waves travel throughout the system at speeds of magnitude  $10^3$  m/s; (4) the process is repeated as soon as new gas lasing media flows into the cavity. An experimental program was initiated to investigate the nature of the acoustic energy put into the laser gas and devices were tested which were designed to remove these disturbances from the system.

## Description of Experiment

Experiments were performed employing a high energy laser of the e-beam electric discharge type having the capability of depositing energy of the order 100-1000 J/l in a single pulse of order  $10^{-6}$  s duration. No attempt was made to extract laser power from the system and net power input to the gas was assumed to equal the electrical input to the cavity.

A closed cycle recirculating system was attached to the laser to move gas through the cavity region at a speed of about 3 m/s. Pressure transducers capable of following the pressure rise associated with shock waves were placed at four locations in the recirculation system. The simultaneous output of all four transducers were recorded on photographs of the four traces made on an oscilloscope.<sup>1</sup>

The recirculating system had provision for introducing acoustic management devices into the recirculator flow. Devices employed included honeycomb structures, screens, and a muffler designed to extract the acoustic energy without introducing a pressure drop in the flow. Since only the muffler proved effective in the tests performed, the muffler design and test results will be discussed in the following section.

#### Muffler Design

The acoustic wave produced by the laser input is represented approximately as a square wave pressure pulse. Since the square wave can be approximated by an infinite series of sine and cosine waves, a muffler must be able to attenuate waves over a wide band in frequency in order to be effective. An additional requirement for the muffler is that it present a low pressure loss to the flow of gas since energy must be expended to counter any pressure drop. In order to satisfy the two major requirements of the muffler, a horn coupled resonator was designed and built. The resonator volume is placed outside the flow field so that interference with the main flow is avoided. An exponential horn is used to couple the resonator volume to the flow since this horn design has the potential to act as a high pass filter. The muffler design is shown in Figure 1.

#### Results

The pressure records were analyzed to find the nature of the acoustic energy produced by the laser pulse and to determine the effectiveness of the muffler in removing the acoustic disturbance. By analyzing the record from two probes mounted a known distance apart, the traveling acoustic wave could be accurately determined. This wave was examined for its frequency content and the results of the power spectral analysis of the laser produced acoustic wave is shown in Figure 2. The results show



that the energy peaks in the 5000 Hz range with a sharp drop off on both sides.

The pressure records were examined to find the effectiveness of the muffler by examining the power spectrum of the wave leaving the muffler. The results of the muffler effectiveness is given in Figure 3 which shows that the muffler attenuated the input wave nearly 40 db at near 500 Hz and 12 db at 5000 Hz. The muffler is found to be effective and to present no measurable pressure drop for the main flow due to the straight pipe design.

#### References

1. Cornelius C. Shih and Gerald R. Karr, "Investigation of Transient Flow and Heating Problems Characteristic of High Energy Laser Gas Circulation Systems," UAH Research Report No. 199, March 1977.
2. C. Cason and T. E. Horton, "Thermal-Acoustical Phenomena in Pulsed High Energy Lasers," AIAA/ASME (78-HT-61), May 1978.
3. Cornelius C. Shih and Charles M. Cason, "Gas Dynamic and Acoustic Management for Visible Wavelength Lasers," SPIE Technical Symposium East '78, Washington, D. C., March 1978.



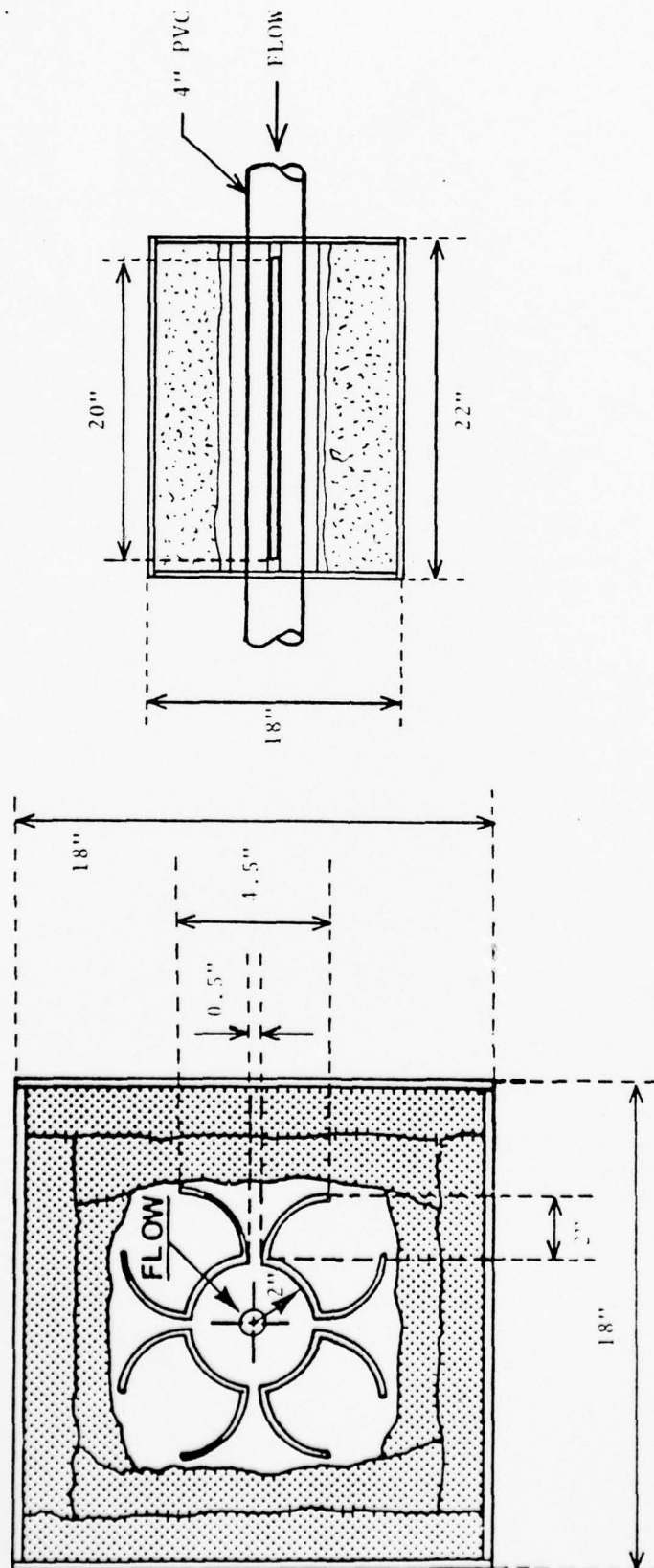


FIGURE 1. MUFFLER DESIGN

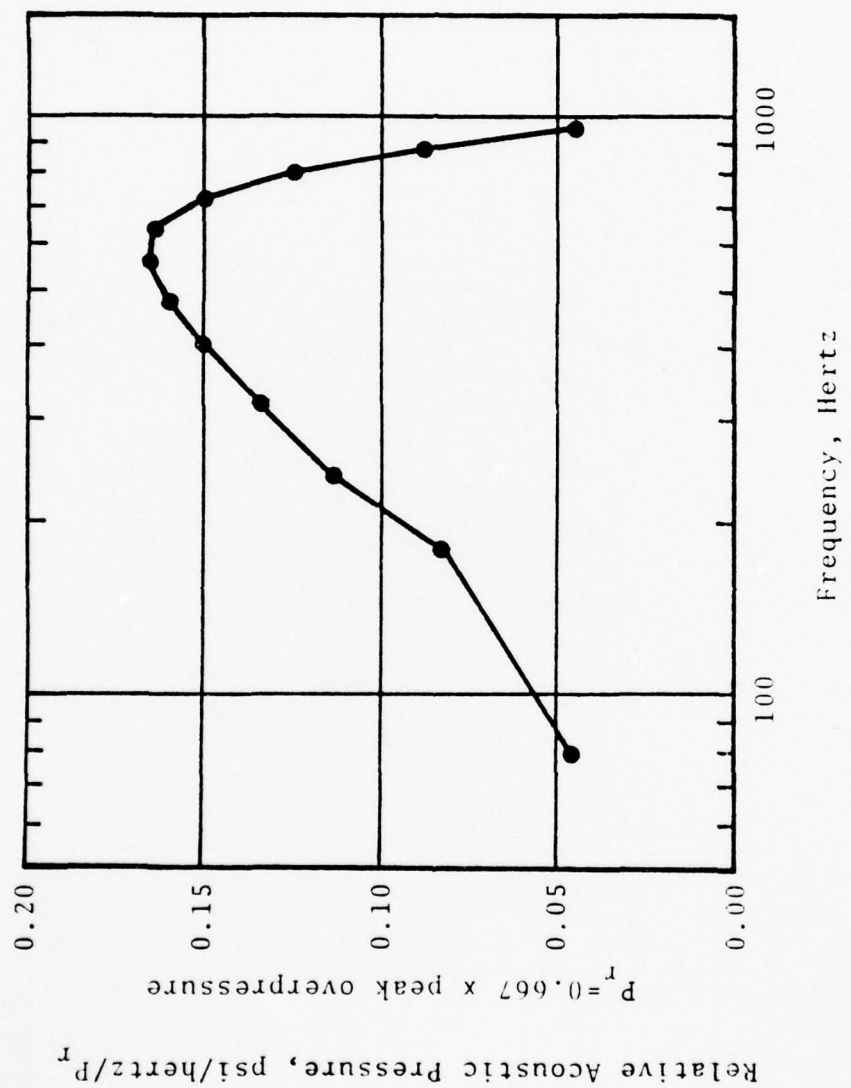


FIGURE 2. ACOUSTIC PRESSURE SPECTRUM RESULTING FROM LASER FIRINGS.

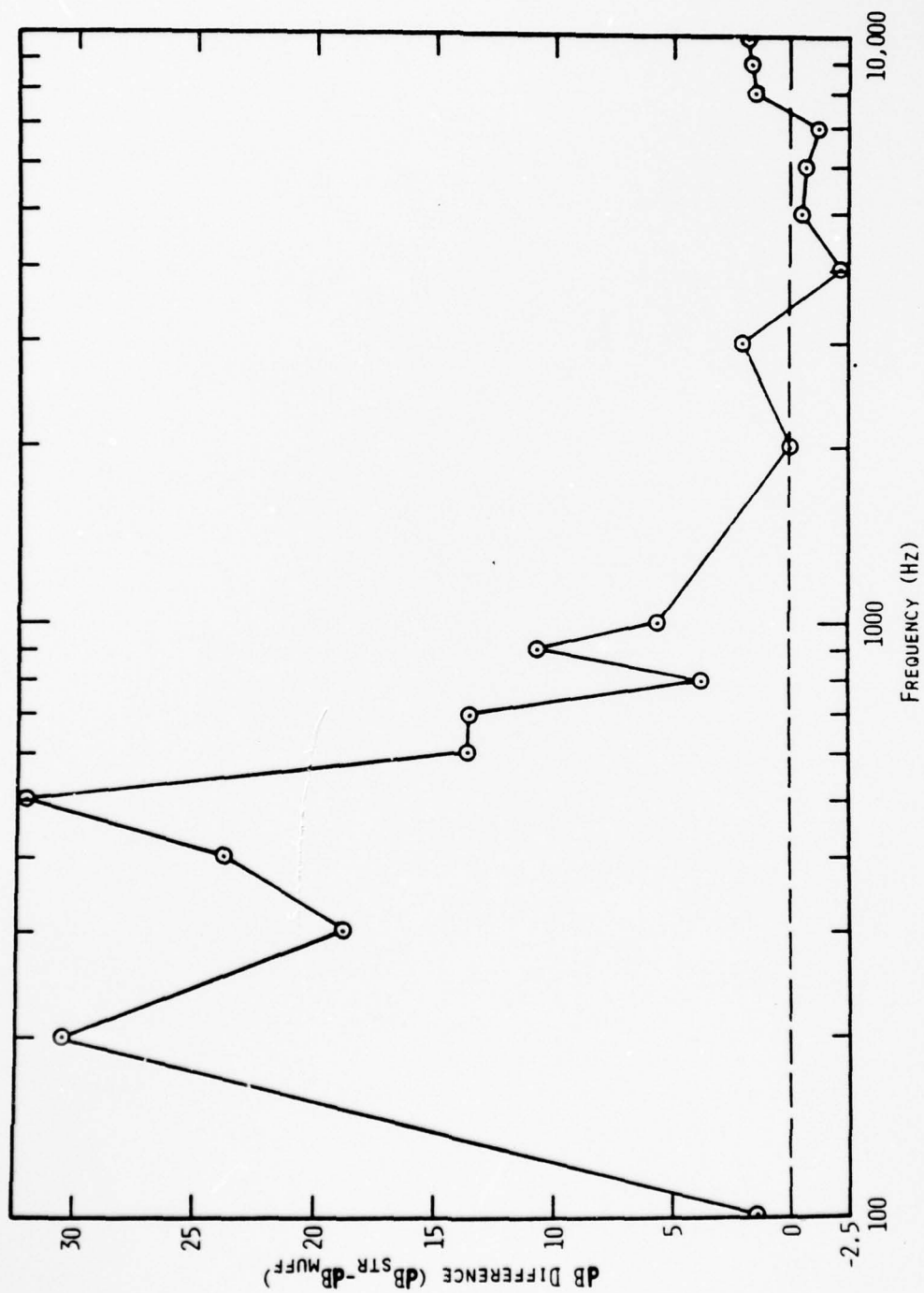


Figure 5. Results of Muffler Attenuation Showing Input Wave at 40 db near 500 Hz and 12 db at 5000 Hz.

AD-A068 547

ALABAMA UNIV IN HUNTSVILLE SCHOOL OF SCIENCE AND ENG--ETC F/G 20/5  
INVESTIGATION OF TRANSIENT FLOW AND HEATING PROBLEMS CHARACTERI--ETC(U)  
MAR 79 C C SHIH, G R KARR, J F PERKINS DAAK40-77-C-0161

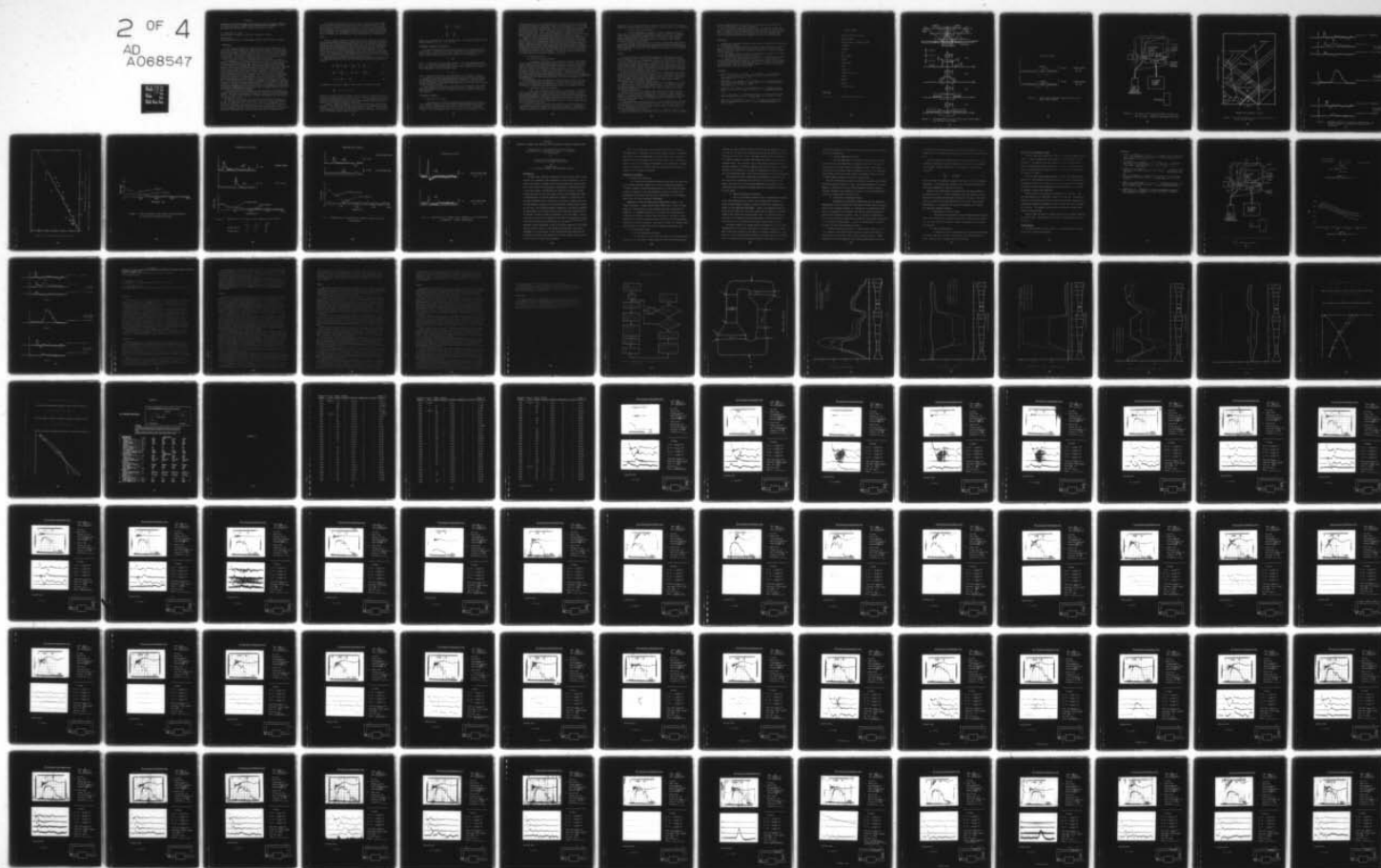
UNCLASSIFIED

UAH-RR-219

DRCPM-HEL-CR-79-8

NL

2 OF 4  
AD  
A068547





### Section 3

Presented at the Joint Meeting of the Acoustical Society of America (ASA) and the Acoustical Society of Japan (ASJ) in Honolulu Nov. 28-December 1, 1978  
NON-LINEAR WAVE PROPAGATIONS IN A PULSED HIGH ENERGY GAS LASER

C. C. SHIH AND G. R. KARR

The University of Alabama in Huntsville, Huntsville, Alabama

CHARLES CASON

US Army Missile Research and Development Command, Redstone Arsenal, Alabama

#### INTRODUCTION

In the recent development of pulsed high energy lasers, problems of non-linear waves of both acoustic and thermal nature propagating in the laser gas media have attracted considerable research interest because of their effects on the fractional density gradient which, in turn, relates to the optical quality of laser beams. One of these lasers uses a closed cycle circulator to provide an acoustically and thermally conditioned flow of the laser gas suitable for lasing at the laser cavity on a continuous basis of operation.

The closed cycle circulator consists of a compressor, heat exchangers, acoustic attenuators, flow regulator and diverter, ducting, control and instrumentation systems along with a laser cavity for the purpose of maintaining a recirculating flow of the laser gas. Reconditioning the laser gas with gas dynamic, acoustic and thermodynamic means is necessitated by the abrupt deposition of energy at a repetitive rate in the recirculating flow of laser gas at the cavity, causing severe spacial and temporal variations of fluid and thermal characteristics throughout the flow. These variations are results of shock waves and expansion waves which propagate away from the cavity, following the e-beam controlled pulsed energy discharge. The transient pressure, temperature, and velocity gradients are responsible for producing acoustical and thermal perturbations which are directly related to density fluctuations of the laser media. Optical beam quality is known to be degraded by the density fluctuations as noted by previous investigations particularly for  $\text{CO}_2$  lasers<sup>(1-5)</sup>. Efficient operation of the laser requires serious attention to gas dynamic, thermodynamic, and acoustic management of the laser media in the recirculating flow system based on meaningful measurements and analysis of fluid and thermal characteristics of the flow in the pulsed laser operation.

A study has been made to determine the characteristics and propagation of the waves generated by the input power pulse characteristic of high energy laser systems. The study has consisted of an analytic prediction based on one-dimensional flow theory and are also used to study the propagation and interaction of the waves with the system.

The sequence of operation of a pulsed high energy gas laser consists of (1) the laser gas media flows in the cavity region; (2) energy is deposited in the gas at a magnitude of  $10^2 - 10^3$  J/l in a total time of magnitude  $10^{-5}$  s; (3) lasing action and laser power extraction occur in total time of magnitude  $10^{-6}$  s; (4) shock waves and expansion waves travel throughout the system at speeds of magnitude  $10^3$  m/s; (5) the process is repeated by the pulse repetition rate which is governed by the flow rate and time needed to dissipate waves.

The quality and magnitude of the laser output is governed by the quality of the flow present in the cavity just prior to the energy deposition. Thus, waves which were generated by the previous laser pulse must be dissipated so that the quality of the flow is not disturbed. The work reported here examines the initial shape of waves generated by the pulse and the changes of this wave as it propagates. This information will find application to the design of devices to dissipate the wave energy by linear and nonlinear wave interactions.

## THEORY

Since the energy deposition in high energy lasers is much faster than the rate at which acoustic signals can travel typical cavity dimensions, the gas is considered to be stationary during the energy input. The net energy into the gas (total input energy minus the laser energy extracted) is then assumed to be represented by an instantaneous, constant volume heating process. The energy deposition causes an instantaneous rise in pressure and temperature in the cavity region. The pressure discontinuity causes shock waves to propagate both upstream and downstream and corresponding expansion waves in towards the cavity center. The expansion waves pass through the cavity and interact with each other and with the hot cold gas interface left by the energy pulse.

These phenomena of nonlinear wave propagations imposed on the laser gas flow are approximately modeled with a set of one-dimensional unsteady equations as follows:

$$\frac{1}{\rho} \frac{\partial \rho}{\partial t} + \frac{u}{\rho} \frac{\partial \rho}{\partial x} + \frac{\partial u}{\partial x} + \frac{u}{A} \frac{\partial A}{\partial x} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = - \frac{1}{\rho} \frac{\partial p}{\partial x} - \frac{u}{2D} \frac{\partial D}{\partial x} \quad (2)$$

$$ds = C_v \frac{dT}{T} - R \frac{d\rho}{\rho} \quad (3)$$

and implicitly the rate of change of entropy may be a function as shown,

$$\frac{ds}{dt} = f(x, t, A, u, s) \quad (4)$$

Numerically solving the above equations with the method of characteristics has yielded a one-dimensional description of the wave formation structure as shown on a time versus displacement plot given in Figure 1. One-dimensional unsteady gas dynamics is successfully employed to predict the pressures, temperatures, and velocities in the various regions of interaction.

A computer program was prepared to solve the one-dimensional unsteady flow equations. The program requires the initial pressure,  $P_0$ , temperature  $T_0$ , and velocity,  $U_0$ , of the gas and the net energy input to the gas,  $Q$ . This is sufficient information to find the pressure and temperature resulting for the energy input for constant volume heating as given by

$$\frac{P_1}{P_0} = \frac{Q}{\rho c_v T_0} + 1$$

$$\frac{T_1}{T_0} = \frac{P_1}{P_0}$$

where  $\rho$  is the density and  $c_v$  the specific heat. The computer program then obtains solutions for  $P_2$ ,  $T_2$ ,  $P_3$ ,  $T_3$ , etc.

#### FUNDAMENTAL FREQUENCY DETERMINATION

The flow axis mode pressure waves are propagated from the generating excitation cavity. Fundamental flow axis mode frequencies of the waves are estimated to first order by the given cavity dimensions and propagation speed as shown in the following equation for an organ pipe open at both ends:

$$f = \frac{C}{2l}$$

where  $f$  denotes the flow axial mode frequency,  $C$  the wave propagation speed, and  $l$  the excitation dimension along the flow. The fundamental flow axis frequency can also be found approximately from the wave pressure trace recorded in one experiment, using the equation below,

$$f = \frac{1}{2\tau}$$

where  $\tau$  represents the period of overall pressure rise as shown in Figure 2.

In order to perform a detailed frequency spectrum analysis of the waves, the method of Fourier Transform Analysis may be employed. A computer program for performing the Fourier Transform Analysis coupled with a A-D converter capable of providing a sufficiently high sampling rate, has been used to analyze the wave frequency spectrum.

Since the gas flow velocity in relatively small circulators is not negligible when compared to the acoustic wave speed, and the pressure probes are mounted stationary in the flow, a Doppler correction is required to the organ pipe equation,

#### EXPERIMENTAL APPARATUS

##### 1. Closed Cycle Circulator

The closed cycle circulator designed and fabricated for this study is a 1-D simulation having a full scale flow axis dimension and a mirror optical axis. It uses a controlled pulsed discharge that is capable of delivering pulsed energy up to 500 Joules per liter in a single pulse of order  $10^{-5}$  s duration. The instrumentation system for transient flow measurements of flow

axis characteristics may be determined at the preliminary level of the full size circulator development. Transverse frequency mode components will be very high in comparison to the flow axis modes. There was no attempt made to extract laser power from the system. Net power input to the gas was assumed to equal the electrical input to the cavity. The cavity region was tightly sealed in all but the flow direction. The cavity had dimensions of 11 cm x 11 cm in the planes perpendicular to the flow direction and a foil length of 45 cm in the flow direction, but e-beam spreading added an additional 10 cm to this length.

Components of this circulator shown schematically in Figure 3 are listed as follows: a blower (Dayton Model 4C108) with a 10 5/8 in. wheel driven by a electric motor of one horsepower operated at 3450 RPM; PVC piping of 4 in. diameter including 1 in. by-pass pipe; e-beam masks for containing the e-beam to within a specified region of the cavity; cavity structures to box in the discharge region in the vertical and longitudinal directions; mufflers; reflectors. The blower is capable of producing flows with velocities up to about 100 ft/sec by adjusting the by-pass pipe. Figure 3 also shows the relative locations of instrumentation probes in section numbers. The e-beam system was manufactured by Systems Science and Software of Hayward, California.

## 2. Instrumentation System

### a) Pressure Measuring Instrument

The pressure transient of up to 10 psi was sensed by the minigage (Kistler Quartz Pressure Sensor Model 201B5) which gives a direct, high level, voltage signal with less than 100 ohms output impedance and high frequency response of 50 KHz and low frequency response of 0.005 Hz. The sensor then converts the pressure into electrical voltage with bias of up to  $11 \pm 2$  volts. The power required by the transducer to the readout equipment is transmitted through the coupler over a single inexpensive cable. This eliminates all of the inherent piezoelectric high impedance problems of electrical leakage, cable noise and signal attenuation and allows the transducers to be used in contaminated environments and with long and moving cables at low noise and without use of charge amplifiers.

The calibration of the transducers was performed at the factory, and the values of the calibration were noted to be, on the average for all probes, 50 mv per psi for the pressure measurement up to 10 psi. The calibration curve relating the voltage output and the pressure is noted to be linear to  $\pm 0.5\%$ .

### b) Temperature Measuring Instrument

Due to the extremely transient nature of temperature variation in the recirculating flow as a result of the pulsed laser operation, a sensor of high frequency response in excess of 500 Hz is considered necessary for the temperature measurement. Search of an adequate sensor resulted in the selection of a hot-wire sensor made of 0.00015 in. diameter tungsten wire coated with platinum powdery film. The hot-wire sensor is connected to the Temperature and Switching Module (Thermo-Systems Model 1040) which is, in turn, connected to the power supply (Model 1031-10A).

The Module consists of a bridge circuit and amplifier in an open loop configuration so the hot-wire sensor which is ordinarily used as an anemometer probe can be switched to function as a resistance thermometer. Since there is a linear proportionality between the voltage output and the temperature, the



calibration can be simply performed by adjusting the zero and gain set potentiometers to a desired temperature range using the calibrate pots of two temperatures.

### c) Velocity Measuring Instrument

For the measurement of velocities, hot-wire probes the same as those used for the temperature measurement is applied. The probe is connected to the constant temperature anemometer module (Model 1010A). The amplified output signal from the anemometer is sent to the Linearizer (Model 1005B) so that the voltage signal is processed in such a way that it became linearly related to velocity of the gas flow.

The use of these modules ensures the frequency response above 500 KHz with power output as high as 1.5 amps. The noise associated with the anemometer is noted to be less than 0.007% equivalent turbulent intensity. Frequency response to the Linearizer is found to be up to 400 KHz and the accuracy of linearization can reach  $\pm 0.2\%$ .

## RESULTS

The wave structure expected from one-dimensional unsteady flow theory is shown in Figures 1 and 4. The shock wave travels at a Mach number of between 1.1 to 1.5 causing pressure, temperature, density, and velocity rises which are a function of the input energy level. The quantities remain constant until reduced by the expansion wave which has traveled from the outer edge of the cavity. They then again remain constant until reduced by other expansion waves which criss-cross the cavity region. The quantities and the times at which the waves arrive at a point are predicted based on the one-dimensional theory, dimensions of the cavity, and the location of the probe.

Figure 5 shows the recorded outputs of pressure, temperature, and velocity probes at various sections in the circulator for a typical firing. The first gauge which is closest to the cavity region is seen to record the expected wave form with sharply defined shock and expansion wave signals. The output of the other two probes show, however, that the wave structure changes to simply a sharp pressure rise followed by a smooth decay.

Figure 6 shows a plot of the results obtained for the pressure rise across the shock wave as a function of input energy density. Also shown is a plot of the results obtained from the one-dimensional computer program. The results show general agreement with the theory. One source of error is due to non-uniform energy deposition.

Figure 7 shows traces of pressure waves measured at position 7, Figure 3, for two levels of power input, 54 and 34 J/l, respectively. Wave frequency spectra of the two waves are also presented as a result of Fourier Transform Analysis. A slight increase in the frequency at higher harmonics was noted due to the decrease in power input. Nonlinear effects are not apparent at the fundamental frequency.

Figure 8 presents pressure wave traces of a wave passing through a  $90^\circ$  bend in the circulator. The wave forms before and after the bend are distinctively altered mostly in the frequency spectra. The wave after the bend seems to reduce its fundamental frequency from about 280 Hz to 230 Hz. No effects are noted at the fundamental frequency.

Figure 9 delineates the attenuation effects of a muffler. Results of the frequency spectrum analysis demonstrate that the muffler is effective in reducing



the wave pressure amplitude by 19 dB in 5.5 flow diameters and changing the frequency distribution at the higher harmonics.

Figure 10 presents temperature traces of the thermal pulse passing (see Figure 1) through a resistive attenuator (Ceramic honeycomb) of 10 cm in thickness. It shows the heat absorbing nature of the honeycomb, signifying that the resistive acoustic attenuator may be used as a heat sink at the same time. Forty cm of material was found to eliminate all traces of the thermal wave.

## CONCLUSIONS

Based on the preliminary results of this study, some qualitative conclusions may be deduced as follows:

a) Nonlinear characteristics of the acoustic waves for excimer levels of input energy are best seen in the frequency distribution of acoustic energy changes in the high harmonics due to the wave propagation in the duct, through bends and mufflers.

b) Only minor changes are found in the fundamental frequency due to form changes and propagation effects in the circulator.

c) Most of the energy is found to be stored in the fundamental frequency.

d) Design of the attenuators for closed cycle circulators should be effective and conservatively based when the fundamental flow axis mode frequency is used and linear acoustic methods are applied. Low pressure loss structures providing about a 40 dB one way attenuation should be effective at relatively high repetitively pulse rate applications.

## REFERENCES

1. Pugh, E. R.; Wallace, J.; Jacob, J. II.; Northam, D. B.; and Daugherty, J. D.: "Optical Quality of pulsed Electron Beam Sustained Lasers." Appl. Optics, Vol. 13, 1974, p. 251.
2. McAllister, G. L.; Draggoo, V. G.; and Egushi, R. G.: "Acoustical Wave Effects on the Beam Quality of a High Energy CO Electric Discharge Laser." Appl. Optics, Vol. 14, 1975, p. 1290.
3. Culick, E. E. C.; Shen, P. I.; and Griffins, W. S.: "Acoustical Waves Formed in an Electric Discharge CO Laser Cavity," AIAA Paper No. 75-851, 1975.
4. Kast, S. and Cason, C.: "Performance Comparison of Pulsed Discharge and E-beam Controlled CO<sub>2</sub> Lasers." J. Appl. Phys., Vol. 44, 1973, p. 1631.
5. Basov, N. G.; Danilychev, V. A.; et al.: "Maximum Output Energy of an Electron-Beam-Controlled CO<sub>2</sub> Laser." Sov. J. Quantum Electronics, Vol. 4, 1975, p. 1414.

## LIST OF SYMBOLS

$A$	area of flow cross section
$C$	speed of sound
$C_v$	specific heat at constant volume
$f$	frequency
$P$	pressure
$Q$	heat
$R$	gas constant
$s$	entropy
$T$	temperature
$t$	time
$u$	velocity
$x$	length in flow axis
$l$	length
$\rho$	density
$\tau$	period
$\delta$	friction factor

### Subscripts

$0, 1, 2, 3 \dots$	regions in the flow field
--------------------	---------------------------

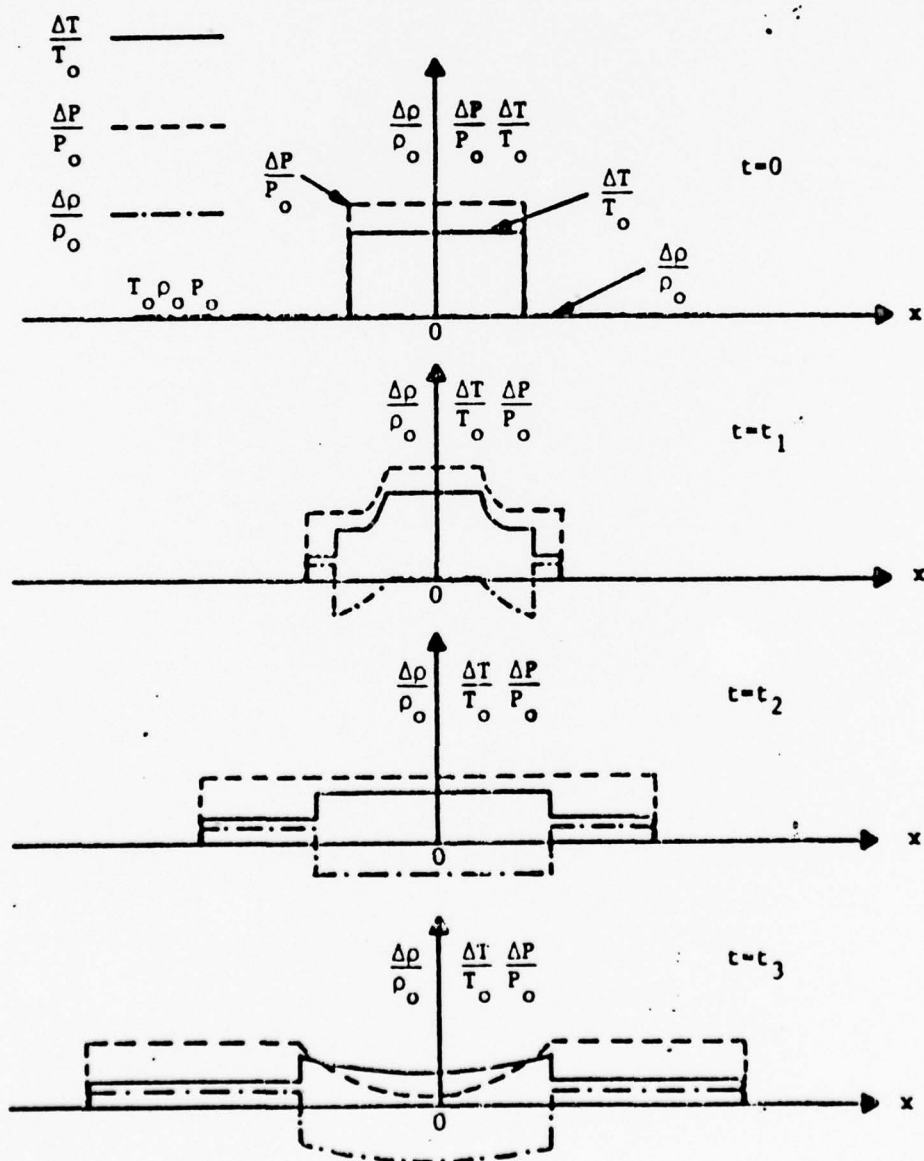
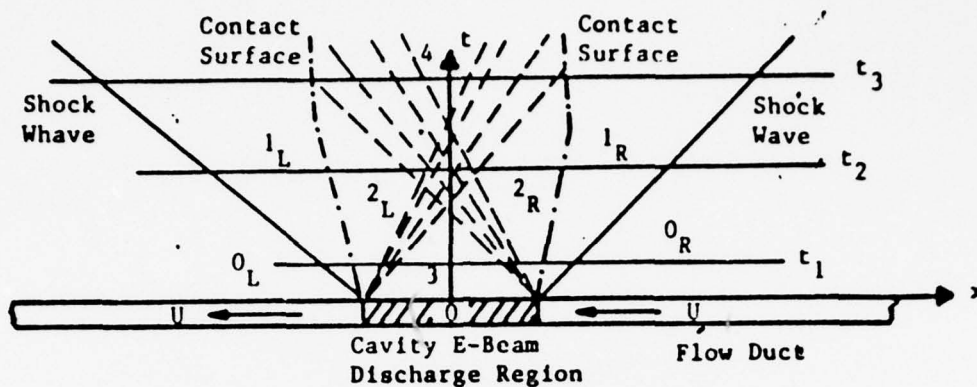


Figure 1. Thermodynamic Property Variations Versus Space for Various Time Frames.

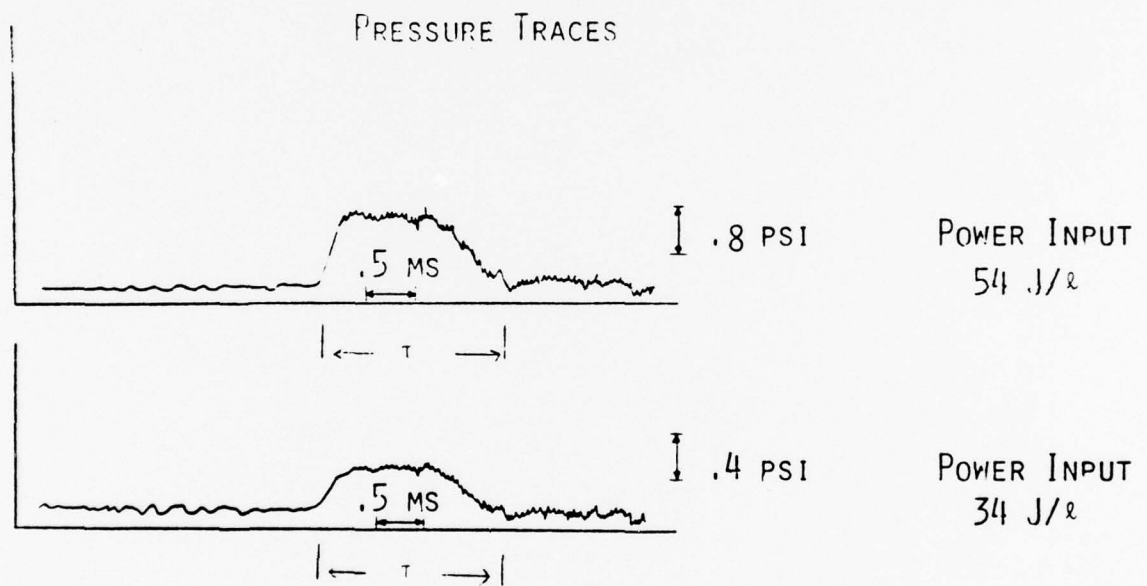


Figure 2. SHOCK WAVE PRESSURE TRACE FOR TWO CAVITY POWER INPUT LEVELS.



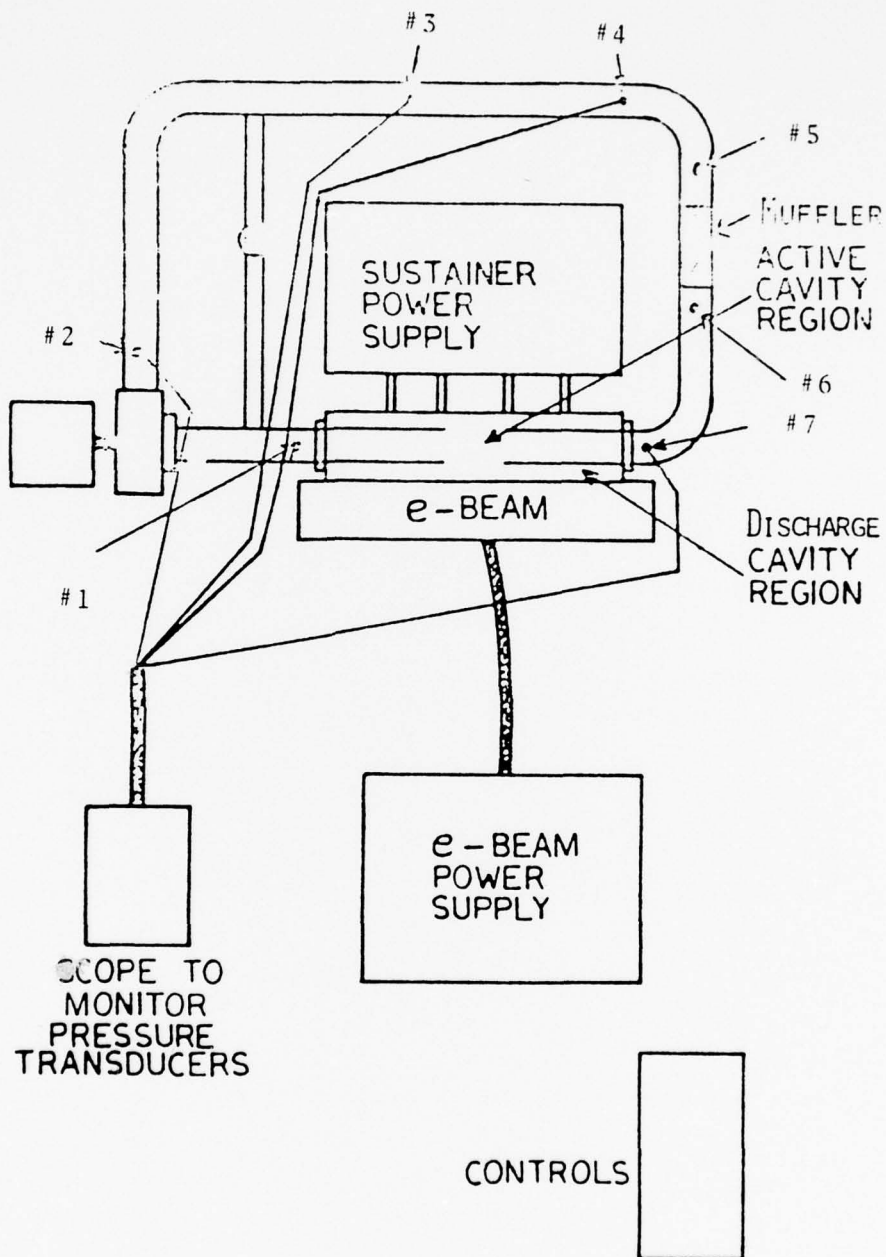


FIGURE 3. TOP VIEW OF PVC SUBSCALE MODEL ATTACHED TO THE S<sup>3</sup> LASER. SYMBOL # INDICATES SECTIONS.

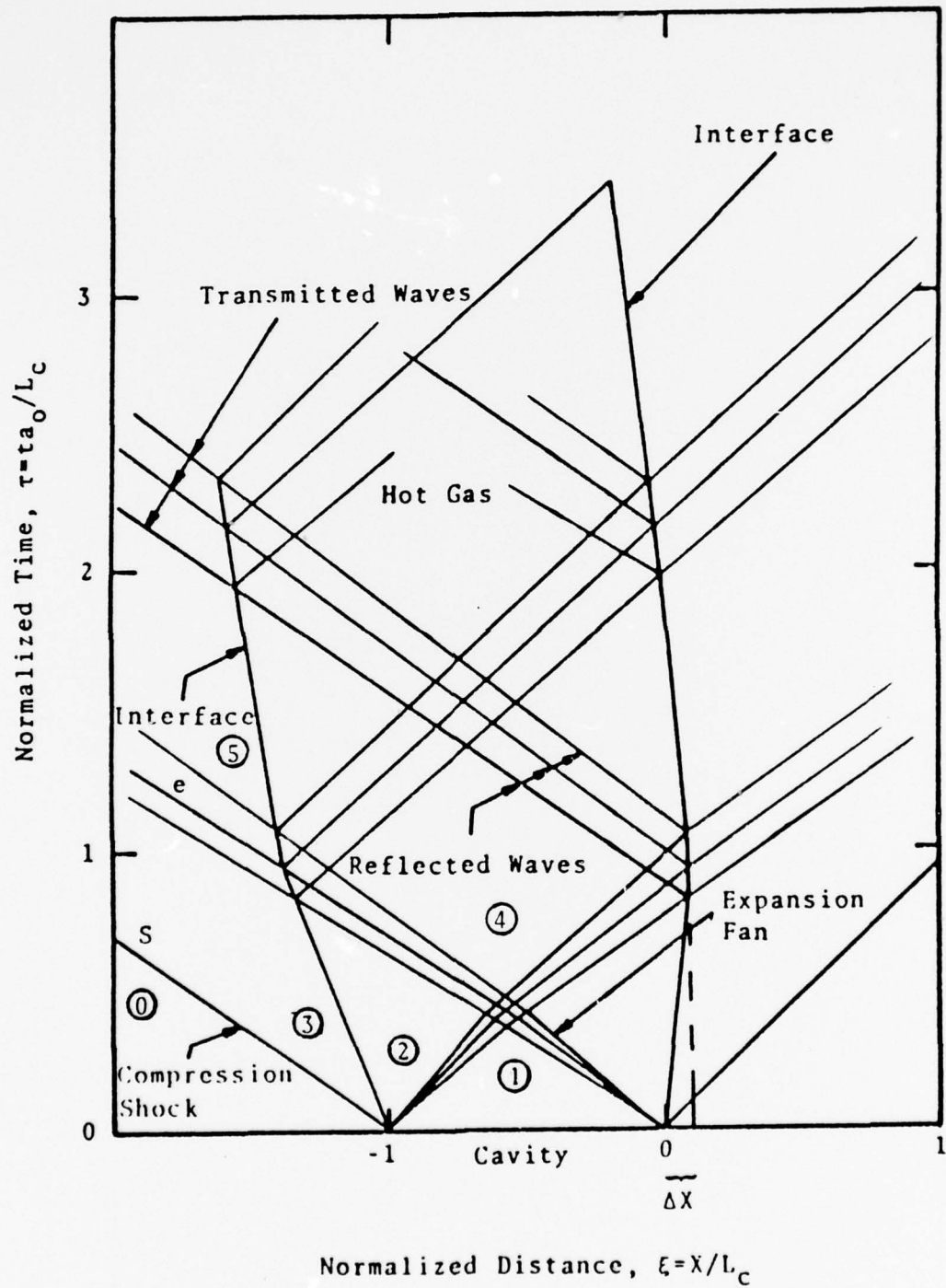


Figure 4. Weight Propagation and Interaction Due to Pulsed Energy Input.

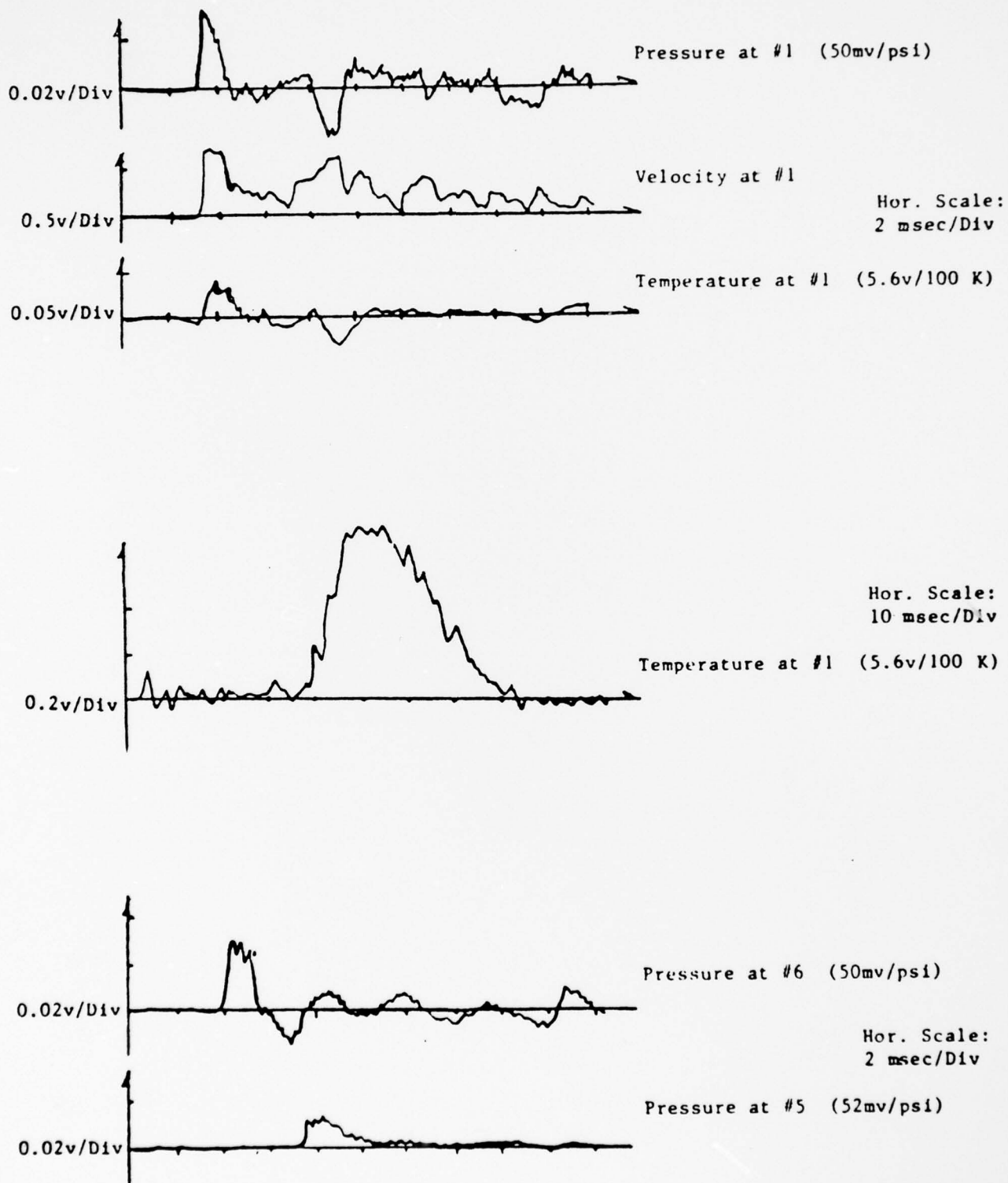


FIGURE 5. RECORDED OUTPUTS OF PRESSURE, TEMPERATURE, AND VELOCITY PROBES AT VARIOUS SECTIONS IN THE CIRCULATOR.

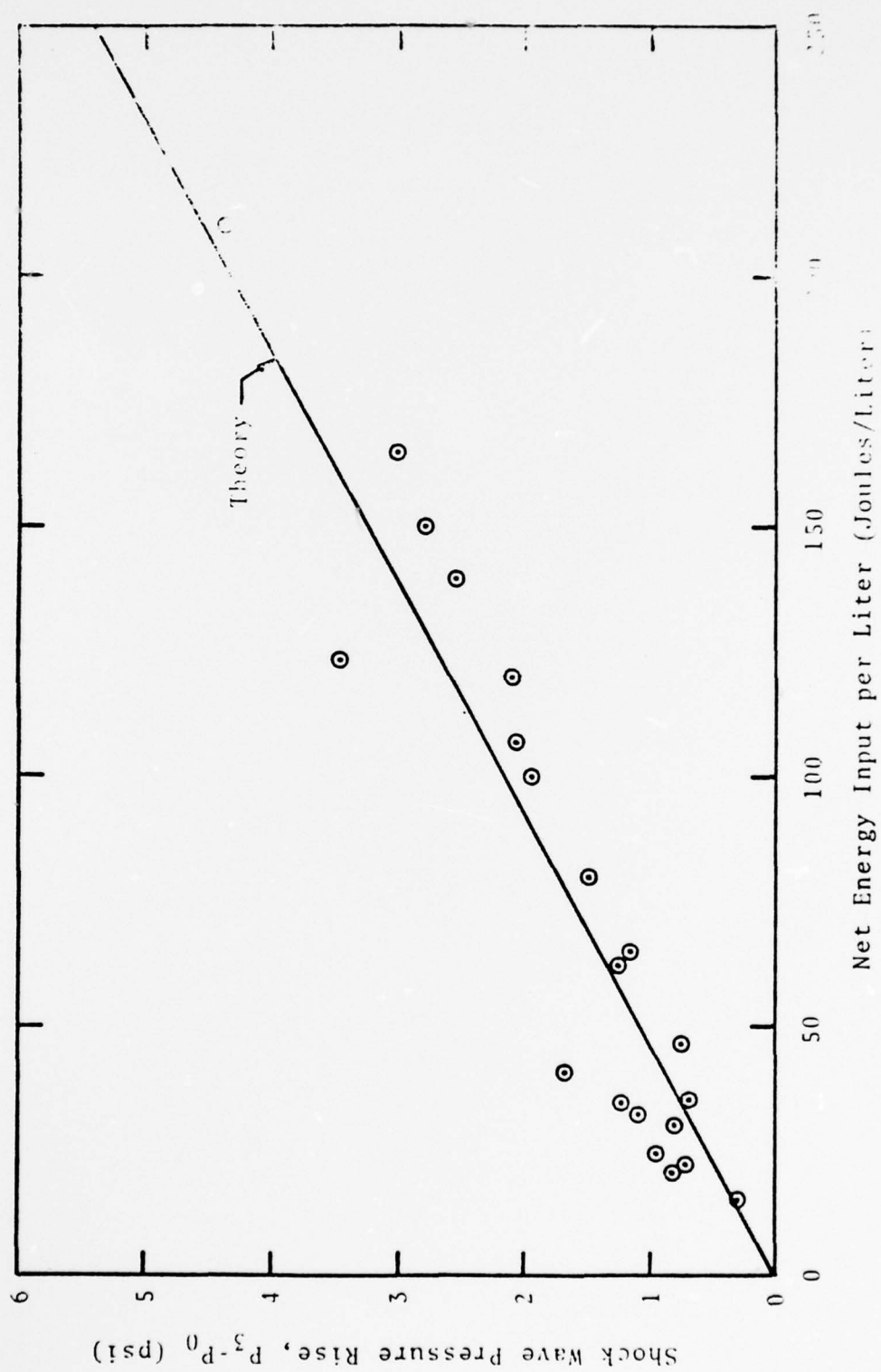


Figure 6. Comparison of Experiment and Theory for Shock Pressure as Function of Input Energy.



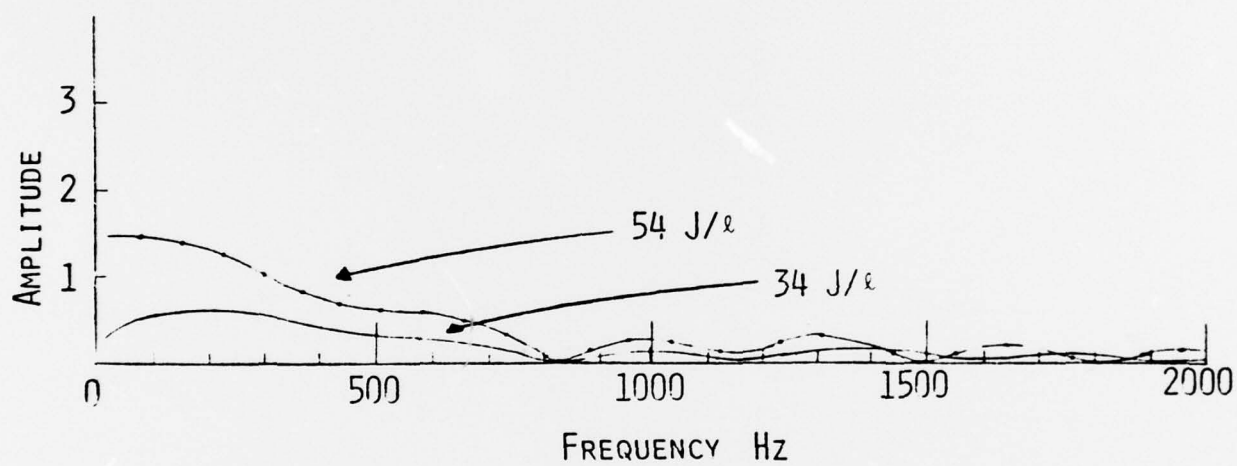


FIGURE 7. WAVE SPECTRUM AT TWO POWER LEVELS DETERMINED BY THE FOURIER TRANSFORM METHOD.

# PRESSURE WAVE TRACES

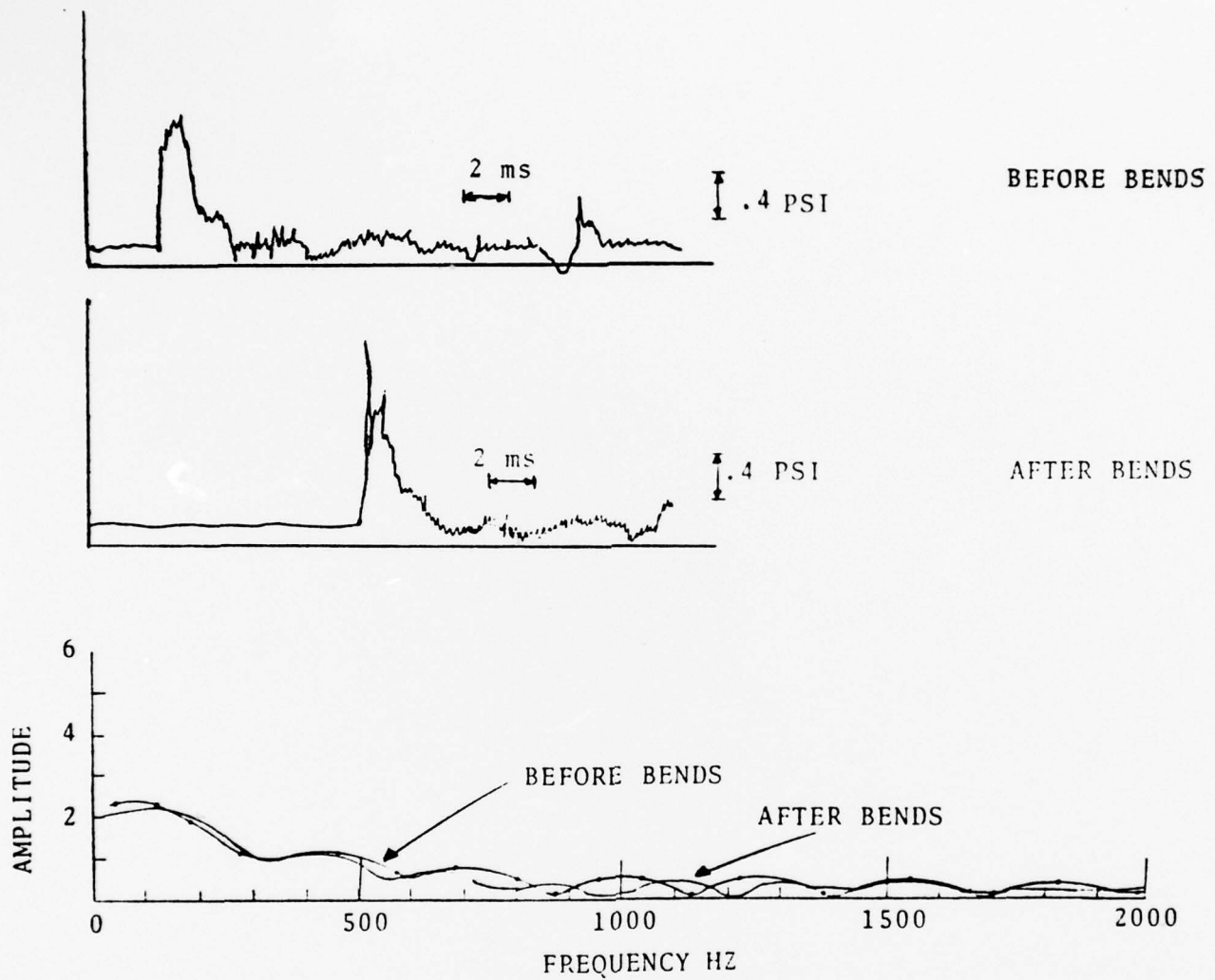


Figure 8. PROPAGATION OF PRESSURE WAVES THROUGH TWO 90° BENDS

	$f$ (Hz)	$f_T$ (Hz)	$f_{FFT}$ (Hz)
BEFORE BENDS	273	312	280
AFTER BENDS	275	277	230

# PRESSURE WAVE TRACES

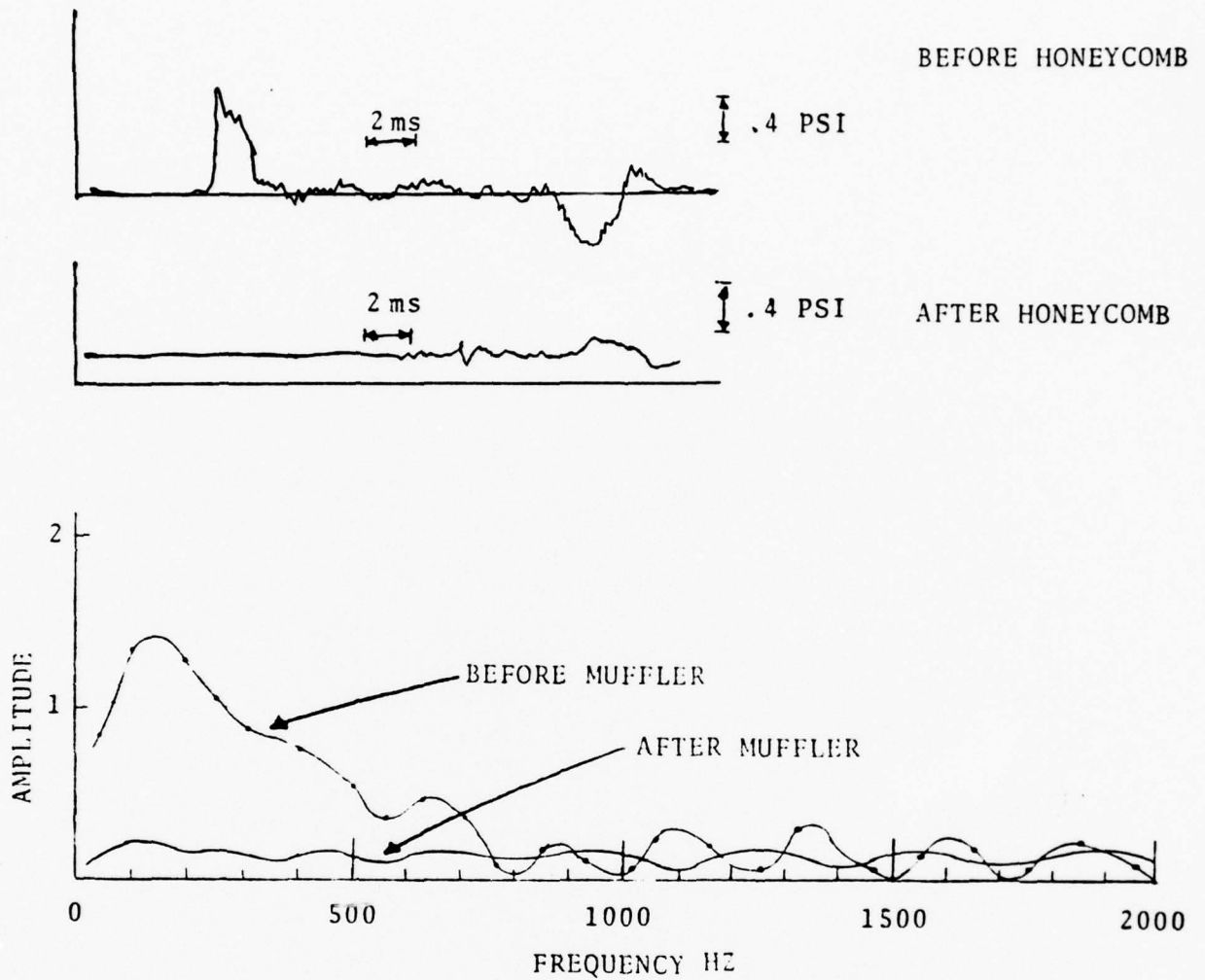


FIG. 9. PROPAGATION OF PRESSURE WAVE THROUGH HORN RESONATOR  
TYPE MUFFLER

TEMPERATURE TRACES

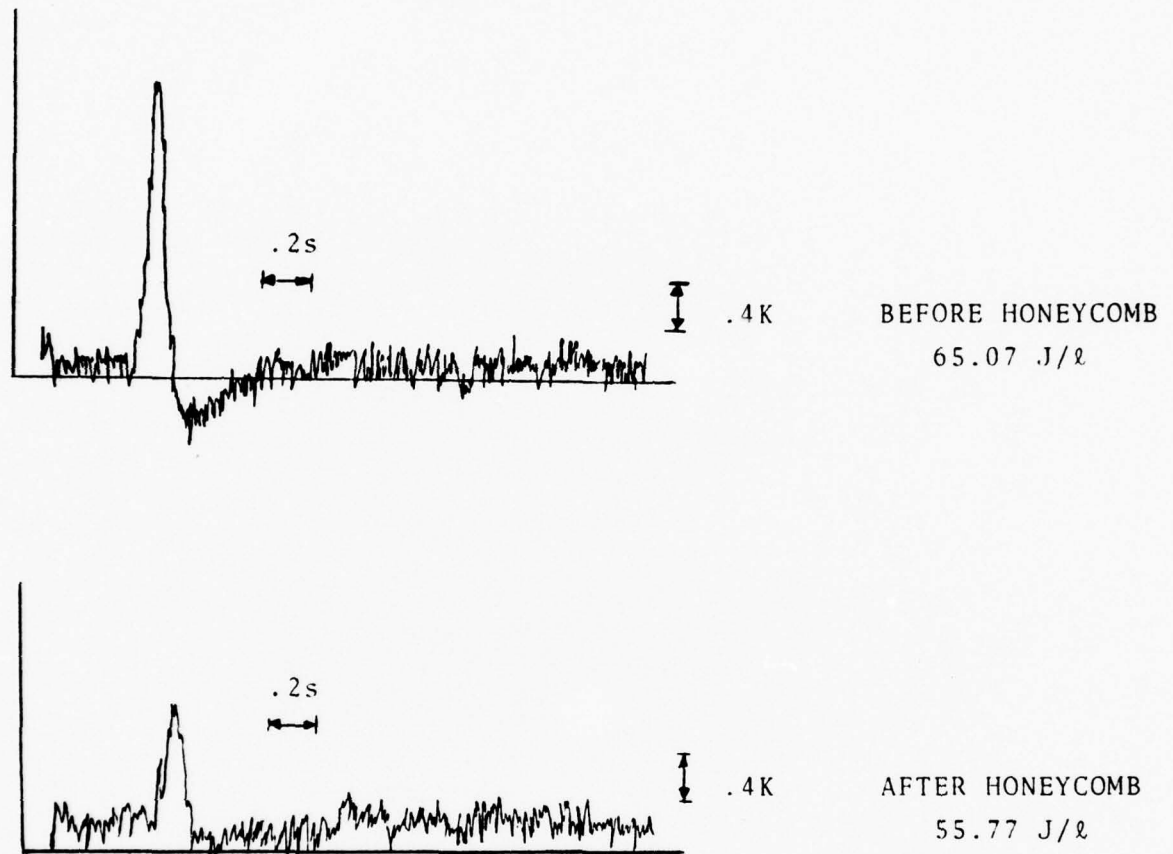


FIG. 10. PROPAGATION OF THERMAL PULSE THROUGH 10 CM OF RESISTIVE ATTENUATOR (CERAMIC HONEYCOMB)

#### Section 4

Presented at Dynamic Flow Conference 1978 in Baltimore, Maryland, September 1978

### Measurements of Fluid and Thermal Characteristics of Recirculating Laser Gas Flows in a Closed Cycle Circulator for Pulsed Lasers

by

Cornelius C. Shih and Gerald R. Karr  
The University of Alabama in Huntsville

and

Charles Cason  
U. S. Army Missile Research and Development Command

#### Introduction

A closed cycle circulator associated with electrically pulsed lasers consists of a compressor, heat exchangers, acoustic attenuators, flow regulator and diverter, ducting, control and instrumentation systems along with a laser cavity for the purpose of maintaining a recirculating flow of laser gas suitably reconditioned for lasing at the cavity. Reconditioning the laser gas with gas dynamic, acoustic and thermodynamic means is necessitated by the abrupt deposition of energy at a repetitive rate in the recirculating flow of laser gas at the cavity, causing severe spatial and temporal variations of fluid and thermal characteristics throughout the flow. The resulting pressure, temperature, and velocity gradients are responsible for producing acoustical and thermal perturbations which are directly related to density fluctuations of the laser media. Optical beam quality is known to be degraded by the density fluctuations as noted by previous investigations particularly for CO<sub>2</sub> lasers<sup>(1),(2),(3),(4),(5)</sup>. Therefore, design improvement as well as efficient operation of the lasers requires serious attention to gas dynamic, thermodynamic, and acoustic management of the laser media in the recirculating flow system based on meaningful measurements and analysis of fluid and thermal characteristics of the flow in the pulsed laser operation.



This paper presents some of the efforts and findings pertaining to the measurements of unsteady flow quantities, namely pressure, temperature and velocity of the recirculating flow in the closed cycle circulator at various locations for several levels of pulsed energy input. Special emphasis is made on the technique development for the measurement of temperature fluctuations in the highly transient flow where high frequency response of the instrument is required.

#### Experimental Apparatus

##### 1) Closed Cycle Circulator

The closed cycle circulator designed and fabricated for this study is of subscale size and intended for use with a single pulse generator ( $S^3$  laser) capable of delivering pulse energy up to 500 Joules per litre, so that the adequacy of the instrumentation system for transient flow measurements of particular interest may be determined at the preliminary level of the full size circulator development.

Components of this circulator shown schematically in Fig. 1, are listed as follows: a blower (Dayton Model 4C108) with a 10 5/8 in. wheel driven by a electric motor of one horsepower operated at 3450 RPM; PVC piping of 4 in. diameter including 1 in. by-pass pipe; E-beam masks for containing the E-beam to within a specified region of the cavity; cavity structures to box-in the discharge region in the vertical and longitudinal directions; mufflers; reflectors. The blower is capable of producing flows with velocities up to about 100 ft/sec by adjusting the by-pass pipe.

##### 2) Instrumentation System

###### a) Pressure Measuring Instrument

The pressure of up to 100 psi was sensed by the mini-gage which gives a direct, high level, voltage signal with less than 100 ohms output

impedance and high frequency response of 50 KHZ and low frequency response of 0.005 HZ. The sensor then converts the pressure into electrical voltage with bias of up to  $11 \pm 2$  volts. The power required by the transducer to the readout equipment is transmitted through the coupler over a single inexpensive cable. This eliminates all of the inherent piezoelectric high impedance problems of electrical leakage, cable noise and signal attenuation and allows the transducers to be used in contaminated environments and with long and moving cables at low noise and without use of charge amplifiers.

The calibration of the transducers was performed at the factory, and the values of the calibration were noted to be, on the average for all probes, 50 mv per psi for the pressure measurement up to 100 psi. The calibration curve relating the voltage output and the pressure is noted to be quite linear.

#### b) Temperature Measuring Instrument

Due to the extremely transient nature of temperature variation in the recirculating flow as a result of the pulsed laser operation, a sensor of high frequency response in excess of 500 HZ is considered necessary for the temperature measurement. Search of an adequate sensor resulted in the selection of a hot-wire sensor made of 0.00015 in. diameter tungsten wire coated with platinum powdery film. The hot-wire sensor is connected to the Temperature and Switching Module (Thermo-Systems Model 1040) which is in turn connected to the power supply (Model 1031-10A).

The Module consists of a bridge circuit and amplifier in an open loop configuration so the hot-wire sensor which is ordinarily used as an anemometer probe can be switched to function as a resistance thermometer. Since there is a linear proportionality between the voltage output and the temperature, the calibration can be simply performed by adjusting the zero and

gain set potentiometers to a desired temperature range using the calibrate pots of two temperatures.

c) Velocity Measuring Instrument

For the measurement of velocities, hot-wire probes the same as those used for the temperature measurement is applied. The probe is connected to the constant temperature anemometer module (Model 1010A). The amplified output signal from the anemometer is sent to the Linearizer (Model 1005B) so that the voltage signal is processed in such a way that it became linearly related to velocity of the gas flow.

The use of these modules ensures the frequency response above 500 KHZ with power output as high as 1.5 amps. The noise associated with the anemometer is noted to be less than 0.007% equivalent turbulent intensity. Frequency response to the Linearizer is found to be up to 400 KHZ and the accuracy of linearization can reach  $\pm 0.2\%$ .

d) Calibration of Temperature Probes

Examination of preliminary experimental data of temperature measurements of the flow laden with shock waves, thermal waves and acoustic waves in the circulator resulted in a finding that the temperature probes were not as sensitive as the pressure and velocity probes responding to waves of high frequency or gradient. Thus, an extensive calibration of the probes to relate the probe characteristics and environmental temperature to the frequency response became necessary for establishing a corrective procedure to ensure the measurement accuracy.

A calibration device consisting of a circular disc with two 1 in. by 1 in. windows at the opposite sides rotating at various fixed speeds, a heated gas flow source and a probe support as shown in Fig. 2. Proper adjustment of the flow temperature and rotation speed enabled the device

to simulate the thermal environments surrounding the probe for a given duration due to the thermal waves and shock waves laden on the recirculating flow.

Based on theoretical consideration of the probe characteristics, instrumental principles and thermal conditions of the flow, it was deduced that the probe frequency response may be delineated by the following equation<sup>(6)</sup>:

$$\frac{T_s}{T_e} = \frac{1}{1 + K \omega} \quad (1)$$

where  $T_s$  denotes the temperature sensed by the probe,  $T_e$  the environmental temperature,  $\omega$  the thermal wave frequency, and  $K$  the probe characteristic coefficient expressed as a function of  $T_e$  and  $\omega$ .

Results of the calibration are presented with the above parameters and variables in Fig. 3. These calibration curves for various  $T_e$  can be applied for correcting the temperature measured by the probe. The coefficient  $K$  was found to be highly dependent on  $T_e$  and  $\omega$  for a given probe. Theoretically, it is known that the smaller the diameter of the probe, the higher the frequency response.

#### e) Calibration of Velocity Probes

The probes were calibrated by using a Thermo-Systems Calibrator (Model 1125) following the furnished instructions. Results of the calibration were analyzed with the aid of a computer programmed for the standard data analysis.

#### f) Data Recording System

To amplify and record experimental data from these measurements with proper time sweep, Tektronix oscilloscope (Type 564-3A74-3B3) with memory, equipped with a Polaroid camera, was employed.

### Presentation of Experimental Data

A typical test run involved the  $S^3$  laser and recording temporal variations of pressure, temperature and velocity at various locations in the circulator. In addition, the laser discharge current was monitored in order to determine the energy put into the laser media. For brevity, few typical recorded data are traced from the oscillograph photos presented in Figures 4, 5, and 6.

Figure 4 shows time-dependent pressure, velocity and temperature at Section 1 in the circulator recorded at Channels 1, 2 and 3, respectively. The sweeping time of 2 m sec per div. in the oscilloscope was fast enough to capture the shock wave propagating at the Mach number of 1.1 in terms of pressure, velocity and temperature.

Figure 5 depicts the passing of a thermal wave at Section 1. The wave was measured to be traveling at about 100 ft. per sec. Diffusion of the wave at the section was noted to be rather significant, resulting in a considerable decrease in temperature ( $24^{\circ}\text{C}$ ) from the one ( $74^{\circ}\text{C}$ ) initiated at the cavity. The volume of the heat gas was diffused to almost three times the initial volume.

Figure 6 shows the decay of pressure waves across a muffler installed in the circulator. More than 19 db in acoustic attenuation was noted for this case.

### Acknowledgement

The research effort of Werner Dahm, Jr. contributed greatly to this project and is hereby acknowledged.



### References

1. Pugh, E. R.; Wallace, J.; Jacob, J. II.; Northam, D. B.; and Daugherty, J. D.: "Optical Quality of Pulsed Electron Beam Sustained Lasers." Appl. Optics, Vol. 13, 1974, p. 251.
2. McAllister, G. L.; Draggoo, V. C.; and Eguchi, R. G.: "Acoustical Wave Effects on the Beam Quality of a High Energy CO Electric Discharge Laser." Appl. Optics, Vol. 14, 1975, p. 1290.
3. Culick, E. E. C.; Shen, P. I.; and Griffins, W. S.: "Acoustical Waves Formed in an Electric Discharge CO Laser Cavity." AIAA Paper No. 75-851, 1975.
4. Kast, S. and Cason, C.: "Performance Comparison of Pulsed Discharge and E-Beam Controlled CO<sub>2</sub> Lasers." J. Appl. Phys., Vol. 44, 1973, p. 1631.
5. Basov, N. G.; Danilychev, V. A.; et al.: "Maximum Output Energy of an Electron-Beam-Controlled CO<sub>2</sub> Laser." Sov. J. Quantum Electronics, Vol. 4, 1975, p. 1414.
6. Fingerson, L. M.: "Parameter for Comparing Anemometer Response." Proc. Symposium of Turbulence in Liquids, University of Missouri, Rolla, Missouri, Oct. 1971.

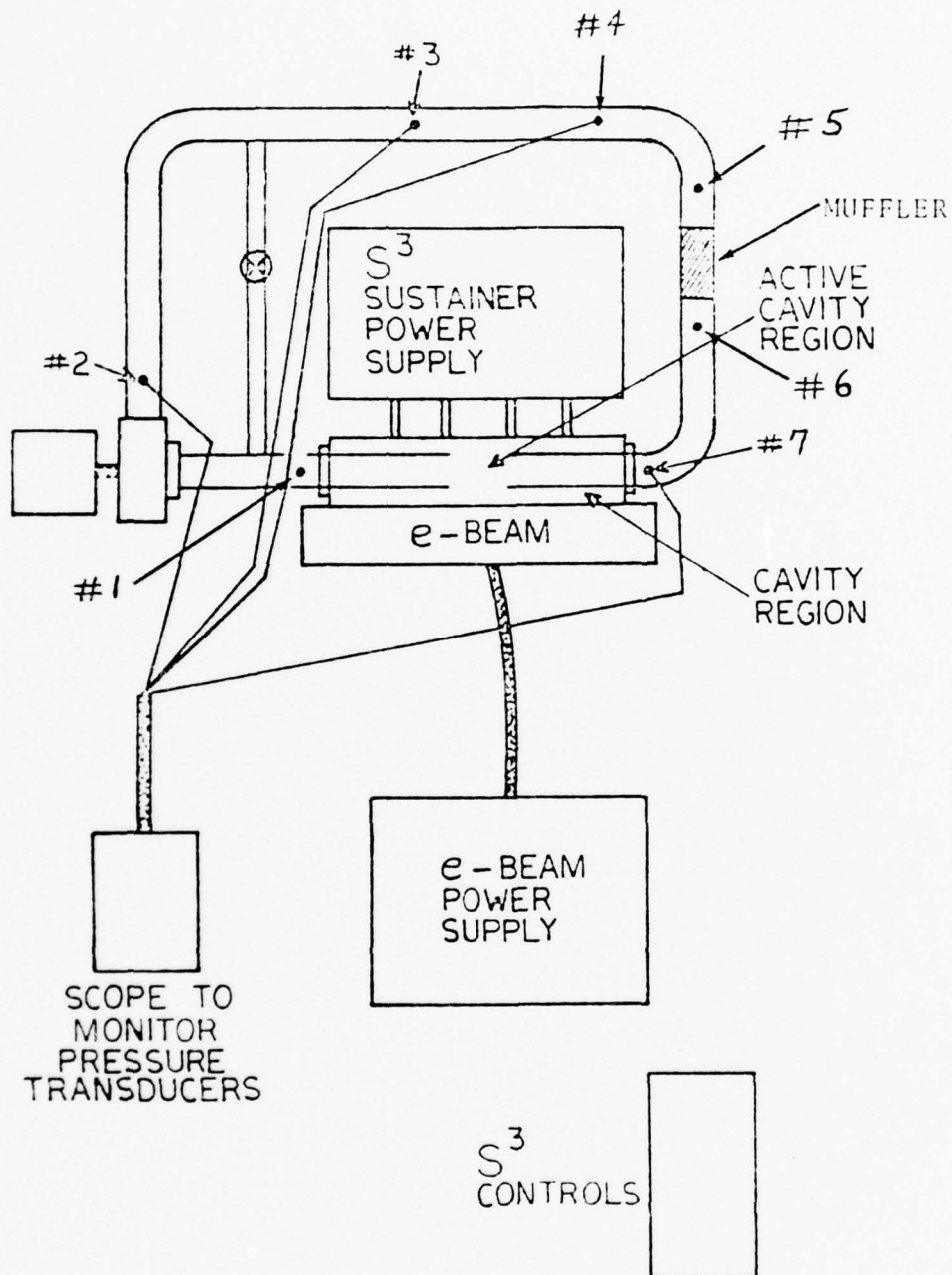


FIGURE 1. TOP VIEW OF PVC SUBSCALE MODEL ATTACHED TO THE  $S^3$  LASER.

Symbol # indicates Sections.

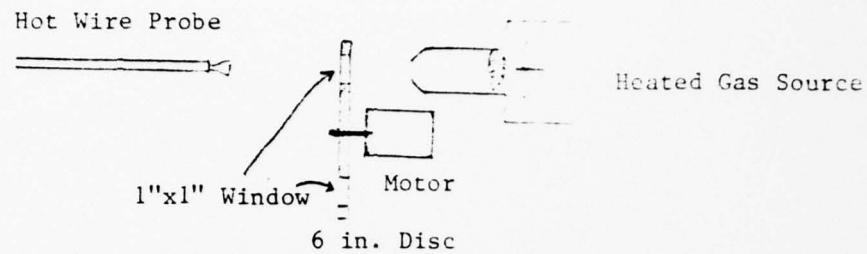


Figure 2  
Temperature Probe Calibration Device

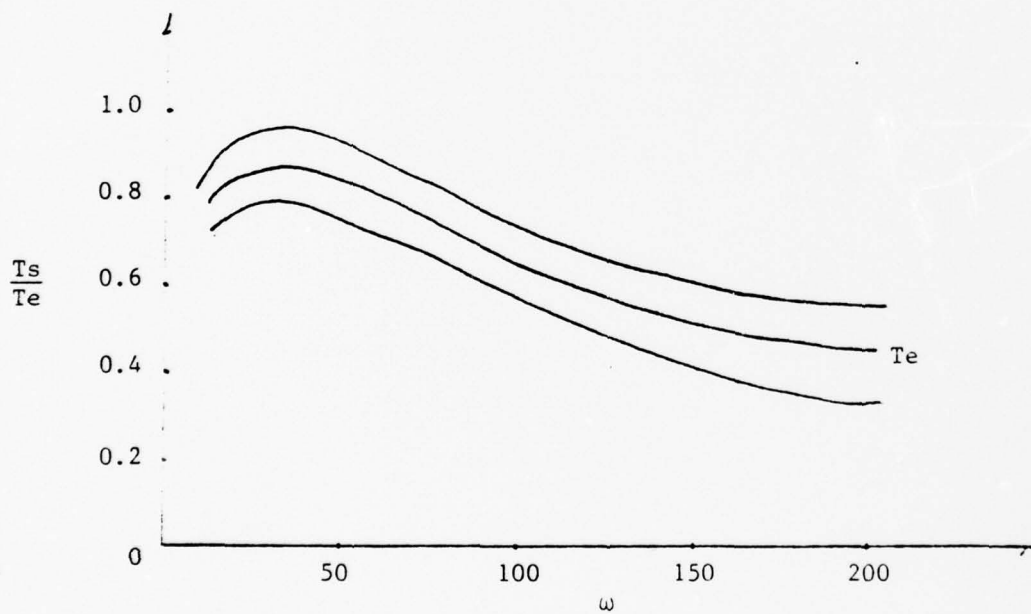


Figure 3  
Temperature Probe Calibration Curves

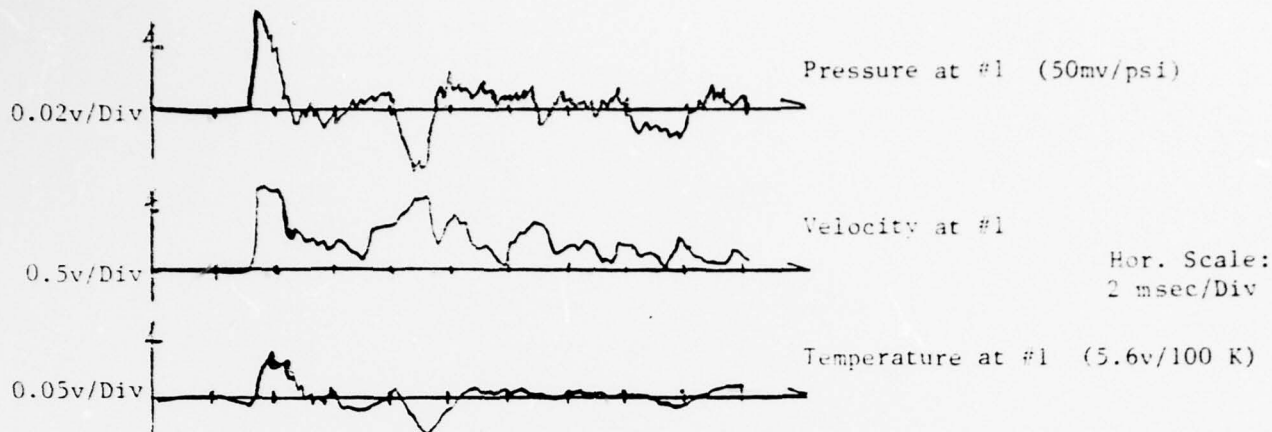


Figure 4

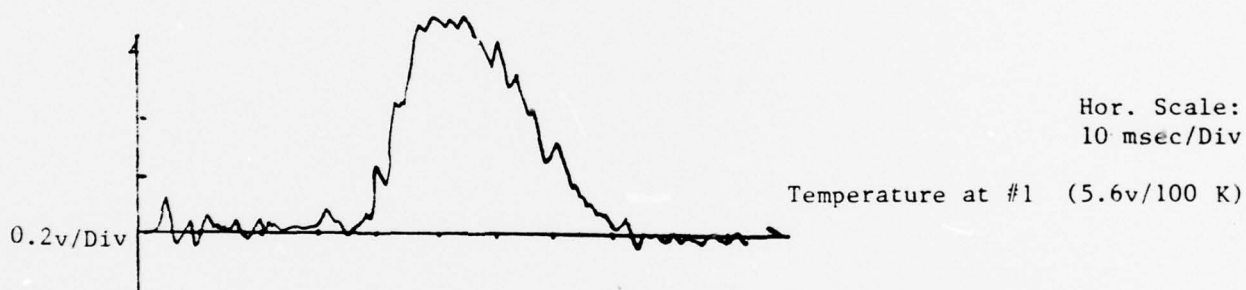


Figure 5

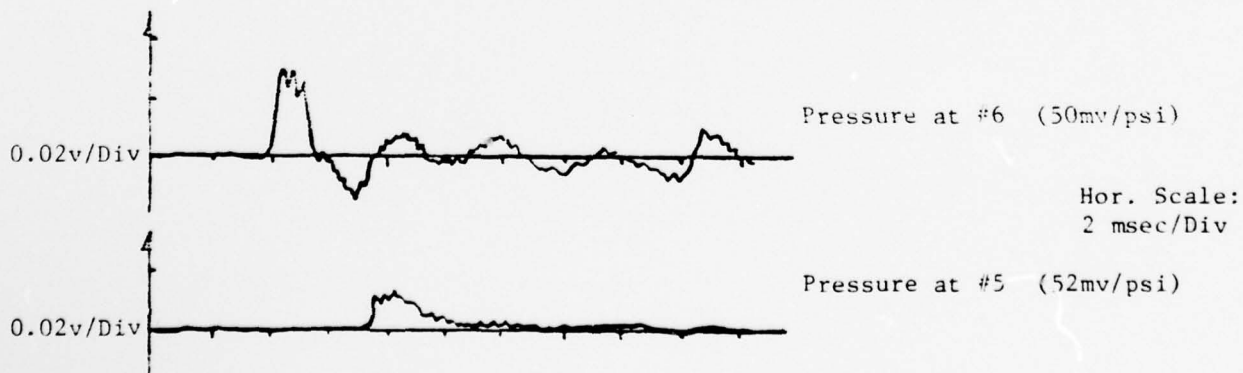


Figure 6

## Section 5

Presented at Second International Symposium on Gas-Flow and Chemical Lasers, Brussels, Belgium, September 1978

### FLUID AND THERMAL CHARACTERISTICS OF CLOSED CYCLE FLOW SYSTEMS FOR HIGH POWER LASERS

G. R. KARR AND C. C. SHIH

The University of Alabama in Huntsville, Huntsville, Alabama

C. M. GASON AND VERNON AYRE

U. S. Army Missile Research and Development Command, Redstone Arsenal, Alabama

#### ABSTRACT

In high power lasers of electric discharge type, the laser gas is recirculated in a closed cycle flow system similar to a subsonic wind tunnel including a laser cavity and heat exchangers. Due to the high heat input at the cavity during the laser operation, peculiar fluid and thermal characteristics have been noted in the closed cycle flow system.

This paper presents a study of these characteristics under steady state operating conditions for various heat input levels and flow parameters, using computer calculation of a one-dimensional model. The computer program has incorporated the characteristics of a specific blower and heat exchanger design and the gas properties of a typical  $\text{CO}_2$  laser gas mixture. Thus, the steady state operating conditions for a given heat input, a given inlet operating pressure and given ambient conditions for the heat exchangers have been determined with the program. Also analyzed are the operating characteristics of the system for off-design conditions. Results of the analysis are presented in terms of velocity, density, temperature, and pressure distributions throughout the system, comparing with a set of standard, nominal operating conditions. This comparison enables an understanding of the changing trends of fluid and thermal characteristics due to the changes of heat input.

Results of this study provide a design tool for the development of a high power laser with optimum efficiency. They also serve as a basis for the investigation of unsteady phenomena using a quasi-steady method of analysis.

#### INTRODUCTION

The high power laser of electric discharge type under this study has the laser gas recirculating in a closed cycle flow system including a laser cavity and heat exchangers. In the laser cavity section, the electric discharge increases the temperature of the laser gas mixture. This increase in temperature will have the detrimental effect of filling the lower energy levels of the  $\text{CO}_2$  and resulting in breakdown of the laser gain unless the gas is cooled or refreshed. Recirculating flow is necessary for sustaining a continuous performance of the laser at high power levels without the need to provide large volumes of gas.

Cooling of the laser gas at a pressure below atmospheric is primarily managed in this system by flow convection which replenish the cavity with cooled gas which has been recycled through the heat exchangers. This method of cooling is superior to the blow-down type or open cycle system from the standpoint of gas economy and other engineering considerations.



The closed cycle flow system is basically similar to a subsonic wind tunnel, but differs from it because of the severe heating and cooling of the recirculating gas under the low operating pressure. Main features of the system are the heating that occurs in the cavity region, the cooling that occurs in the heat exchangers, and the blowers which maintain the flow.

The objectives of this study are: to develop a computer model which is capable of calculating fluid and thermal conditions of the recirculating flow at various stations in the closed cycle and which is capable of simulating major element arrangements and ranges of input parameters; to verify the model with experimental data collected from a limited experiment to evaluate feasibility of the recycling concept; and to estimate the limit of the operating range of such a system.

## METHOD

Coupling the one-dimensional equations of continuity, motion, energy, heat transfer for heat exchangers, compressor performance, and gas kinetics at the laser cavity, a computer program was developed to perform calculations converging on a steady-state operation solution for a closed cycle flow system defined in terms of laser output power and efficiency, gas composition, tunnel heat exchangers, and external radiators, tunnel dimensions, diffuser pressure loss coefficients, blower performance data, coolant flow rates, and a definition of the external heat sources couples to the coolant flow. The steady state solution is obtained for a fixed inlet density or pressure at the cavity entrance. A simplified flow chart of the computer program is presented in Figure 1 to describe the flow of calculations.

With reference to the flow chart in Figure 1, the calculation is started by inputs of initial assumed values throughout the system. Since the steady state operating characteristics are dependent upon the system performance, only one flow variable can be specified at one location in the system. In many high energy systems, the cavity inlet pressure or density is used to control the system and that is why one of these properties is chosen as specified to begin the calculation. Based on the assumed input flow parameters, the gas thermodynamic and physical properties are calculated and all heat exchanger friction factors and heat transfer coefficients are computed.

The gas enters the cavity region and is subjected to the severe heating characteristic of high energy laser system. The cavity area change in the flow direction may be of arbitrary shape or one which provides for constant Mach number through the cavity region. The duct flow losses and heat exchanger induced changes in pressure and temperature are calculated. Performance curves of the blower then provides values for the outlet pressure and temperature for assumed mass flow rate. Additional duct flow and heat exchanger losses are calculated to give flow properties at the cavity inlet. If the calculated and assumed inlet properties differ, a new flow rate and inlet temperature is chosen and the process repeated until convergence is reached. Computation of system energy balance and blower total pressure matching with the system resistance are included. Specific heats, viscosity, and heat transfer coefficients are recalculated as the computation proceeds.

With the ambient air temperature, pressure, and relative humidity given, convergence of the calculations is attained when changes in 16 system temperatures and supplementary pressure, density, temperature, velocity, and Mach number loops fall within prespecified tolerances. The closed cycle flow system under study is shown schematically in Figure 2, with the identification numbers representing the stations where computer calculations are performed.

In the numerical scheme of solving the set of heat-balance and flow equations representing the laser gas flow recirculating with a heat input at the cavity, the Wegstein method of iteration was employed along with the initial forcing

condition that inlet parameters are equal to outlet parameters in the closed loop. When the inlet flow conditions are fixed, the laser power output and efficiency, liquid coolant flow rate, gas properties and system geometry are determined, then a solution for the required heat exchanger effectiveness as well as the number of heat transfer units, and for the blower pressure ratio can be deduced.

## RESULTS

Simulation of a high energy  $\text{CO}_2$  electric discharge laser with an e-beam was employed to illustrate the steady state operation of such a system. The results are presented in Figures 3 through 7 for the system velocity, density, total temperatures, static pressure, and total pressure, respectively. The inlet static pressure is kept the same in these results.

Figure 3 shows the velocity values obtained from the steady state program for 3 ranges of heat deposited in the cavity region (zero, nominal, and twice nominal). The velocity at the cavity inlet for the nominal case is used to non-dimensionalize the results which are plotted relative to the location around the recirculation system. At the bottom of the figure is a drawing of the one-dimensional cross section of the system used in the computation. The cavity cross section was taken as constant for the results presented here. The heat addition at the cavity is seen to cause increased velocity in the system up to the first heat exchanger. The high velocity/high temperature gas encounters increased resistance at the first heat exchanger as the heat input to the system is increased.

Figure 4 shows the values of density throughout the system with the density at the cavity inlet for the nominal-heat case used to non-dimensionalize the results. The results show that the total integrated mass in the system decreases as the heat input to the cavity is increased. During start up of the system from a zero heat input to the cavity, the results show that gas will have to be taken from the system if constant inlet pressure is used as a control for the system.

Figure 5 shows a plot of the total temperature throughout the system using a format similar to Figures 3 and 4. As expected, heat deposited in the cavity causes an increase in the total temperature of the gas. The first heat exchanger removes the majority of the heat in the example considered here. The blower is seen to increase the total temperature of the gas. This temperature rise is removed by the second heat exchanger.

Figure 6 shows a plot of the static pressure throughout the system for the three heating cases. The pressure at Station 1 is the same for all the cases. Limited experimental data was available from the system under simulation and the results are shown on this figure by the dark circles. The results show good agreement for the zero heat case except near Station 3 which is the region of the  $180^\circ$  turning of the flow.

Figure 7 shows the results of the computer simulation for total pressure for the zero and nominal heating case only. The major losses in the system with no heating are seen to be at the two heat exchangers. The losses in the ducts and turning regions are seen to be small. For the nominal heating case, there is an added significant loss of total pressure in the cavity region which the blower must overcome. The heating in the cavity acts as a load on the system which requires added blower power.

Figures 8 and 9 are results of the investigation of the effect on operating conditions for off nominal heating and inlet pressure, respectively. In Figure 8, the inlet pressure is held constant as the heat input is varied. The resulting changes in inlet velocity, temperature, and mass flow rate are plotted as a function of the variation in heating. The results of Figure 8 show that the velocity and mass flow rate decrease while the temperature of the inlet

condition that inlet parameters are equal to outlet parameters in the closed loop. When the inlet flow conditions are fixed, the laser power output and efficiency, liquid coolant flow rate, gas properties and system geometry are determined, then a solution for the required heat exchanger effectiveness as well as the number of heat transfer units, and for the blower pressure ratio can be deduced.

## RESULTS

Simulation of a high energy  $\text{CO}_2$  electric discharge laser with an e-beam was employed to illustrate the steady state operation of such a system. The results are presented in Figures 3 through 7 for the system velocity, density, total temperatures, static pressure, and total pressure, respectively. The inlet static pressure is kept the same in these results.

Figure 3 shows the velocity values obtained from the steady state program for 3 ranges of heat deposited in the cavity region (zero, nominal, and twice nominal). The velocity at the cavity inlet for the nominal case is used to non-dimensionalize the results which are plotted relative to the location around the recirculation system. At the bottom of the figure is a drawing of the one-dimensional cross section of the system used in the computation. The cavity cross section was taken as constant for the results presented here. The heat addition at the cavity is seen to cause increased velocity in the system up to the first heat exchanger. The high velocity/high temperature gas encounters increased resistance at the first heat exchanger as the heat input to the system is increased.

Figure 4 shows the values of density throughout the system with the density at the cavity inlet for the nominal-heat case used to non-dimensionalize the results. The results show that the total integrated mass in the system decreases as the heat input to the cavity is increased. During start up of the system from a zero heat input to the cavity, the results show that gas will have to be taken from the system if constant inlet pressure is used as a control for the system.

Figure 5 shows a plot of the total temperature throughout the system using a format similar to Figures 3 and 4. As expected, heat deposited in the cavity causes an increase in the total temperature of the gas. The first heat exchanger removes the majority of the heat in the example considered here. The blower is seen to increase the total temperature of the gas. This temperature rise is removed by the second heat exchanger.

Figure 6 shows a plot of the static pressure throughout the system for the three heating cases. The pressure at Station 1 is the same for all the cases. Limited experimental data was available from the system under simulation and the results are shown on this figure by the dark circles. The results show good agreement for the zero heat case except near Station 3 which is the region of the  $180^\circ$  turning of the flow.

Figure 7 shows the results of the computer simulation for total pressure for the zero and nominal heating case only. The major losses in the system with no heating are seen to be at the two heat exchangers. The losses in the ducts and turning regions are seen to be small. For the nominal heating case, there is an added significant loss of total pressure in the cavity region which the blower must overcome. The heating in the cavity acts as a load on the system which requires added blower power.

Figures 8 and 9 are results of the investigation of the effect on operating conditions for off nominal heating and inlet pressure, respectively. In Figure 8, the inlet pressure is held constant as the heat input is varied. The resulting changes in inlet velocity, temperature, and mass flow rate are plotted as a function of the variation in heating. The results of Figure 8 show that the velocity and mass flow rate decrease while the temperature of the inlet

gas increases as the heat input to the cavity is increased.

Figure 9 shows the results on velocity, temperature, and mass flow rate (for constant cavity heating at the nominal value) as the inlet pressure varies. The results show that all three quantities increase as the pressure at the cavity inlet is allowed to increase.

#### CONCLUSIONS

The results presented in dimensionless form for general application serve as an important tool in the engineering design of high energy laser system. The results also provide an understanding of the means for controlling inlet conditions which, in turn, control the laser output performance. For example, Figures 8 and 9 reveal that inlet temperature control requires pressure and heat input variation of opposite sign for stable control.



# COMPUTER PROGRAM FLOW CHART

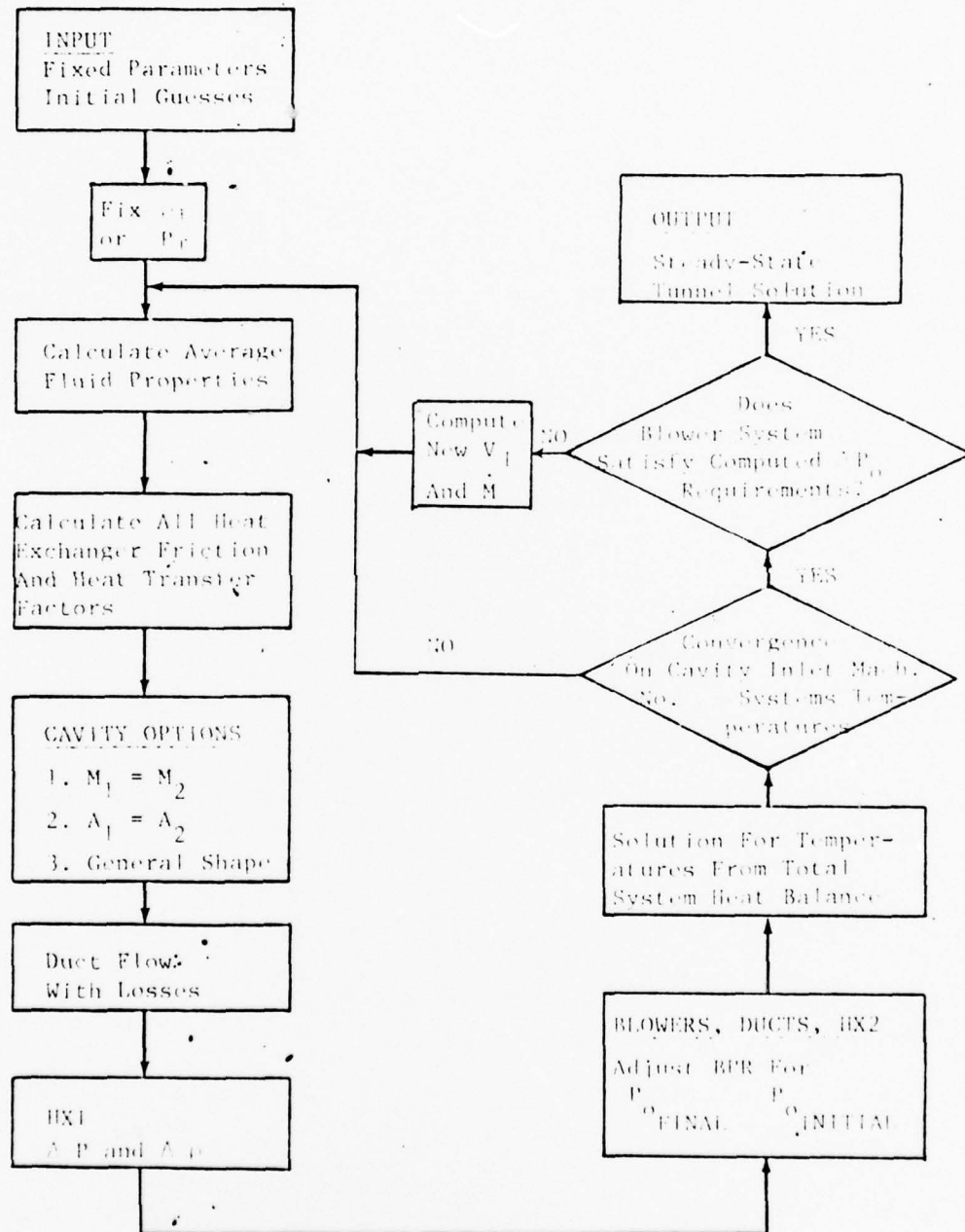
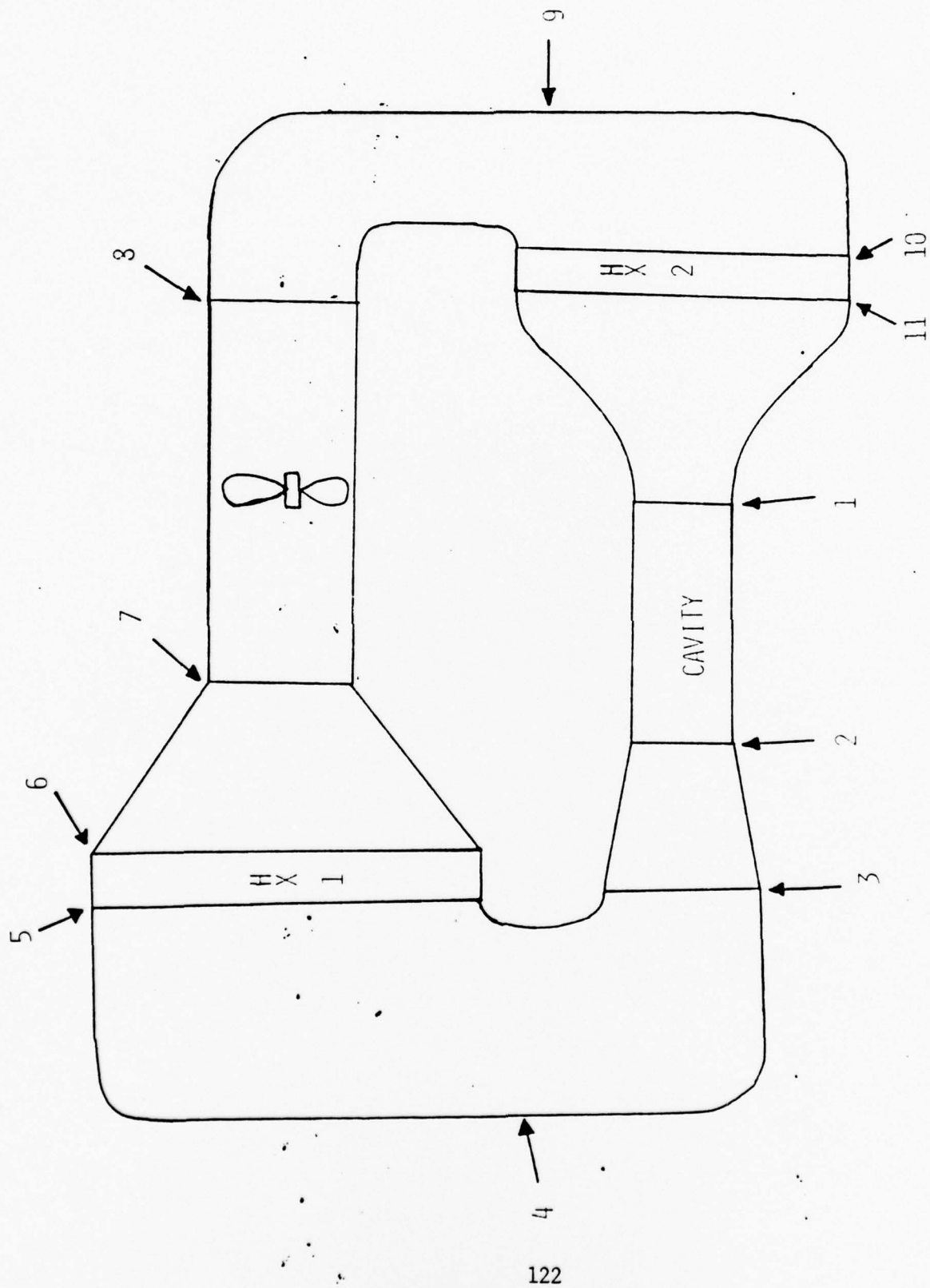


Figure 1. Flow Chart of Computations for Steady State Operation of Recirculator.





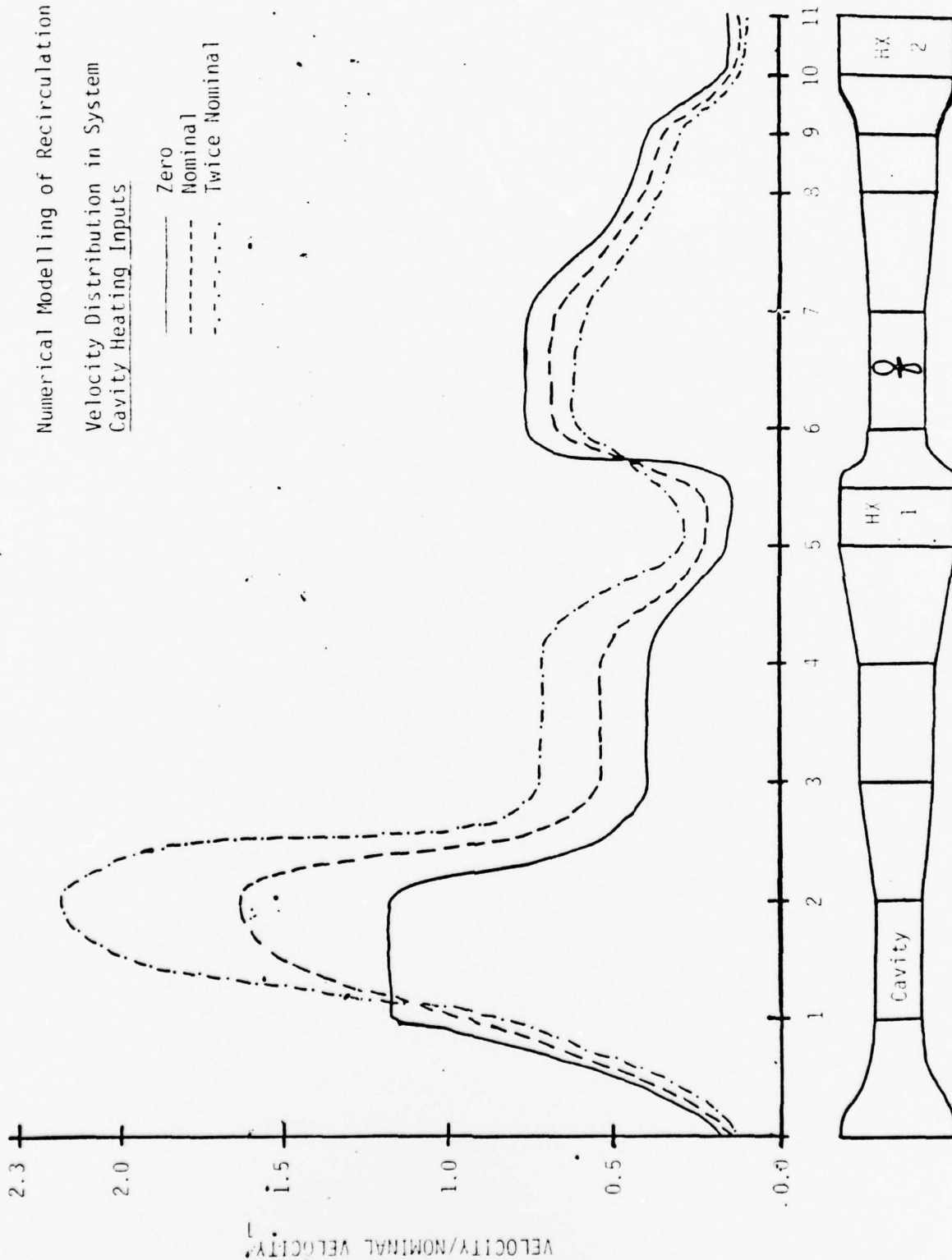
WIND TUNNEL SCHEMATIC

Figure 2. Recirculating System Section Numbering.

# Numerical Modelling of Recirculation System

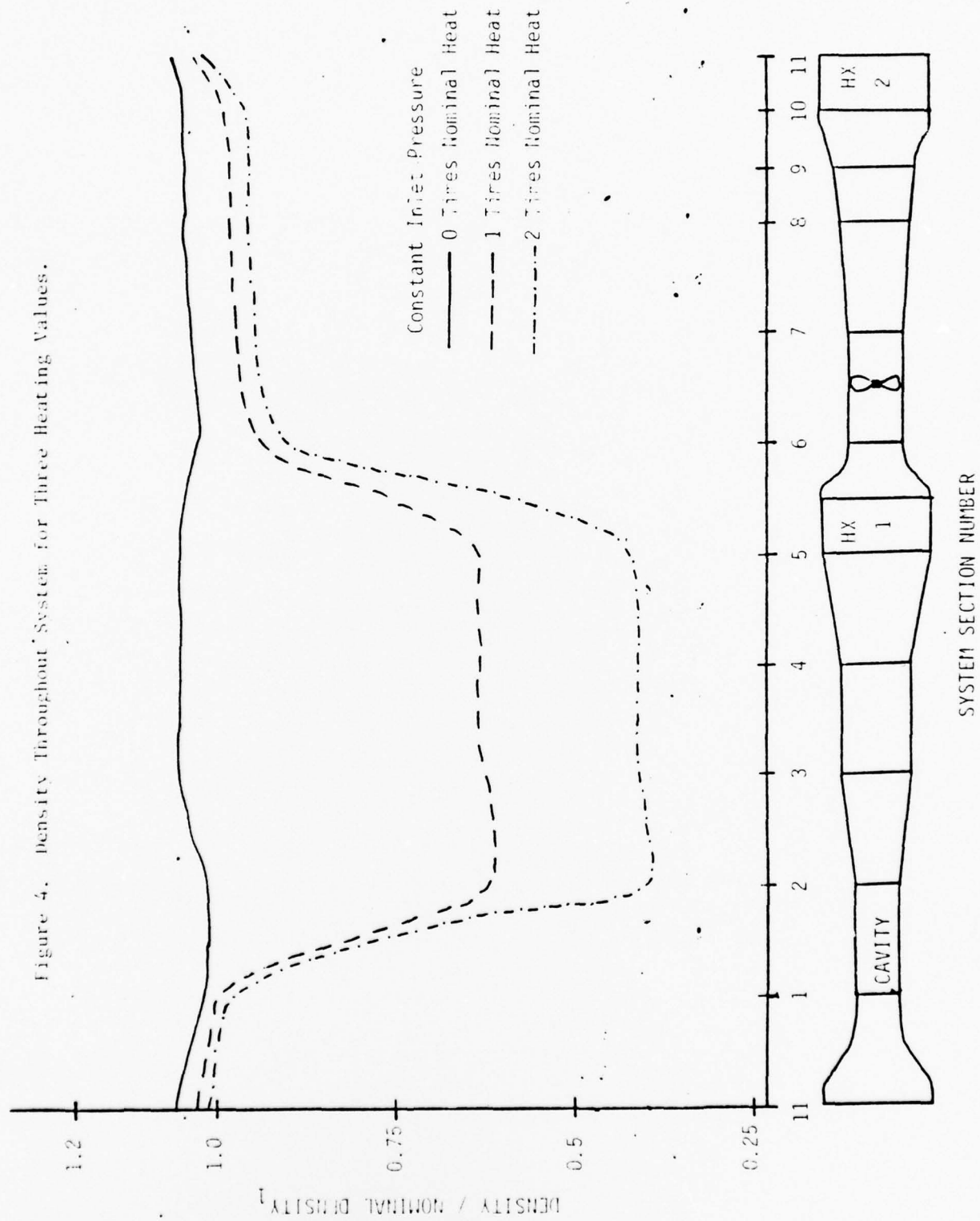
Velocity Distribution in System  
Cavity Heating Inputs

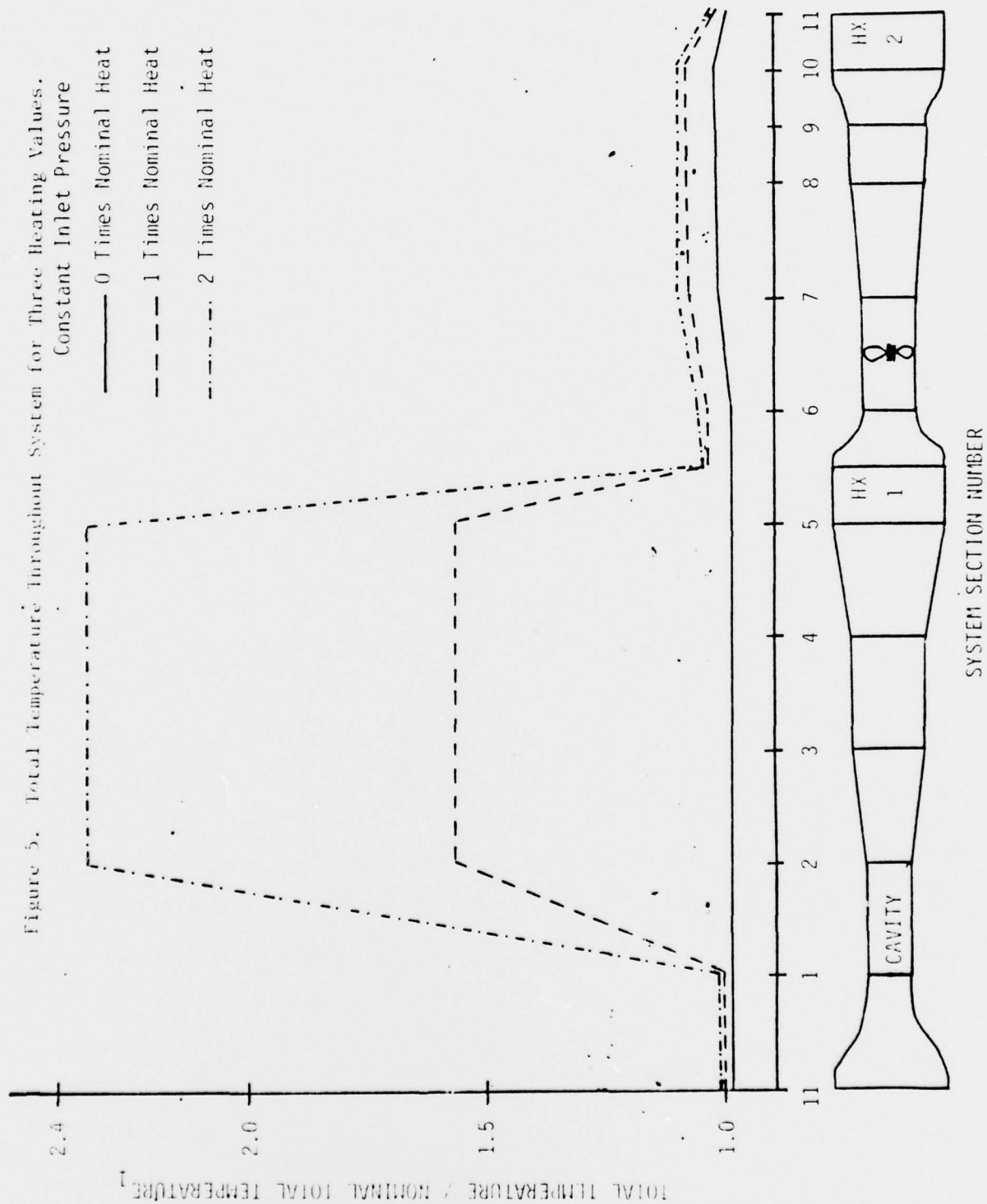
— Zero  
- - - Nominal  
- . - . - Twice Nominal

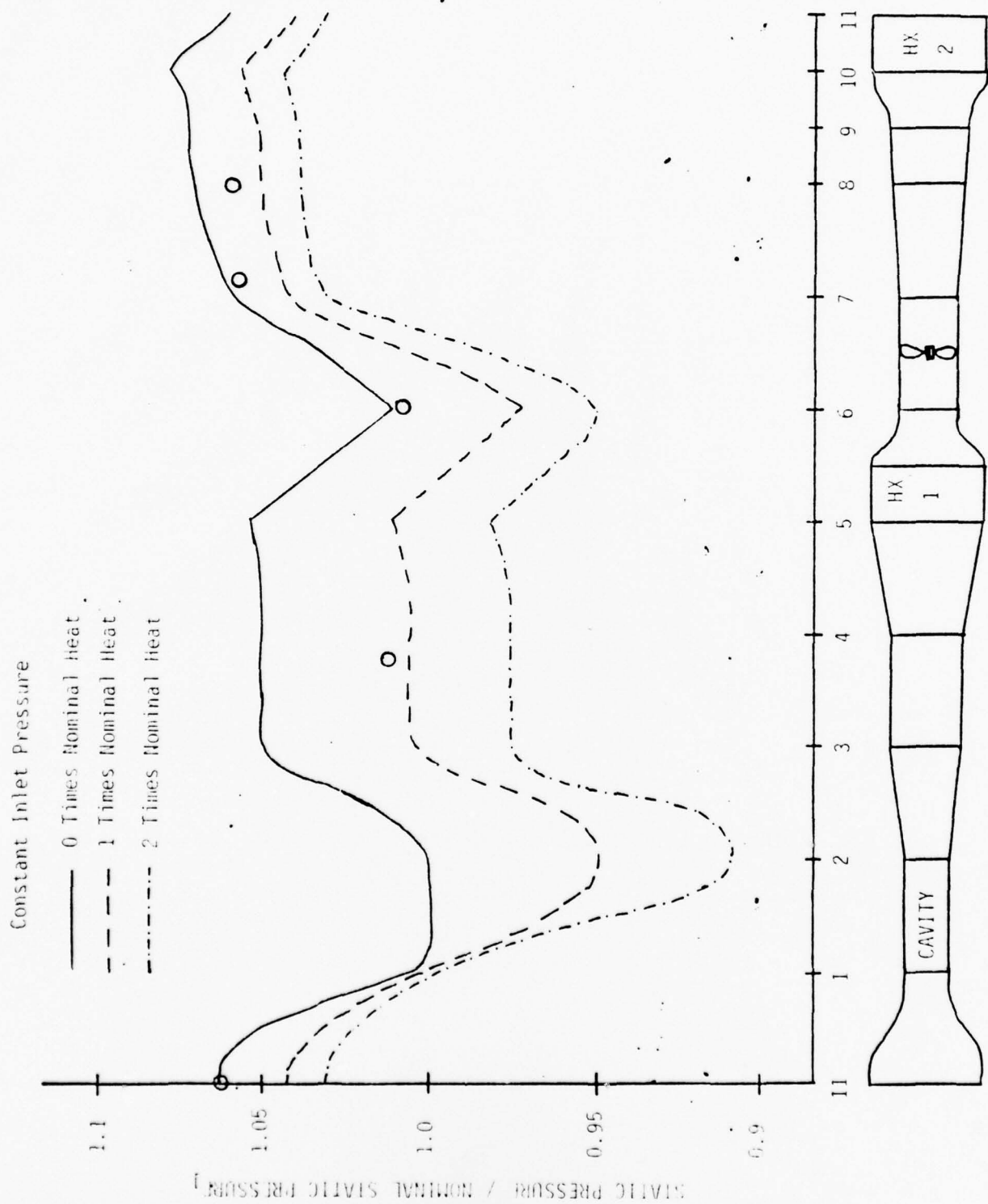


SYSTEM SECTION NUMBER  
Figure 3. Velocity Throughout System for Three Heating Values.

Figure 4. Density Throughout System for Three Heating Values.





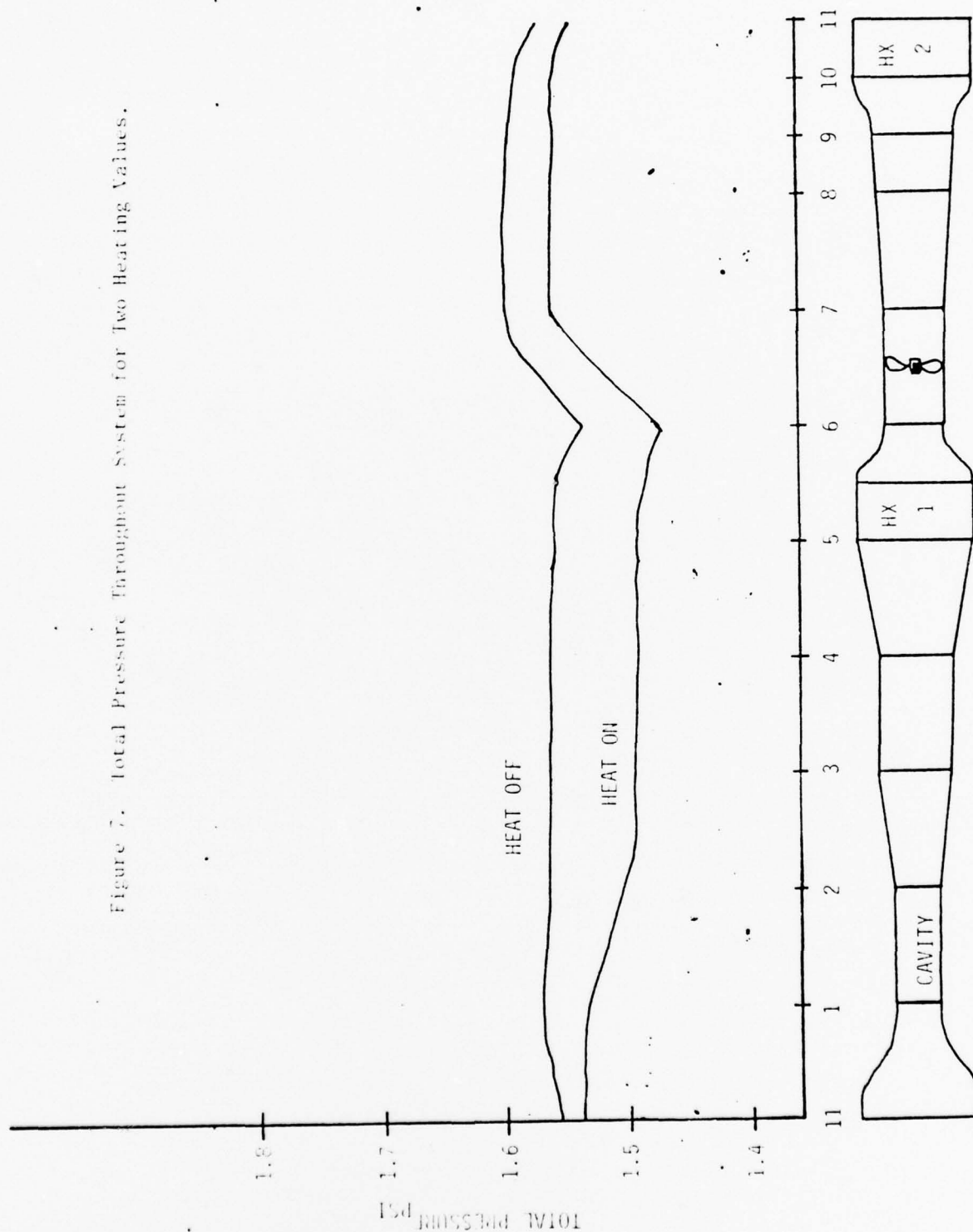


SYSTEM SECTION NUMBER

Figure 6. Static Pressure Throughout System for Three Heating Values.



Figure 7. Total Pressure Throughout System for Two Heating Values.



SYSTEM SECTION NUMBER

Figure 8. Variation in Inlet Velocity, Temperature, and Mass Flow Rate Versus Heating Values.

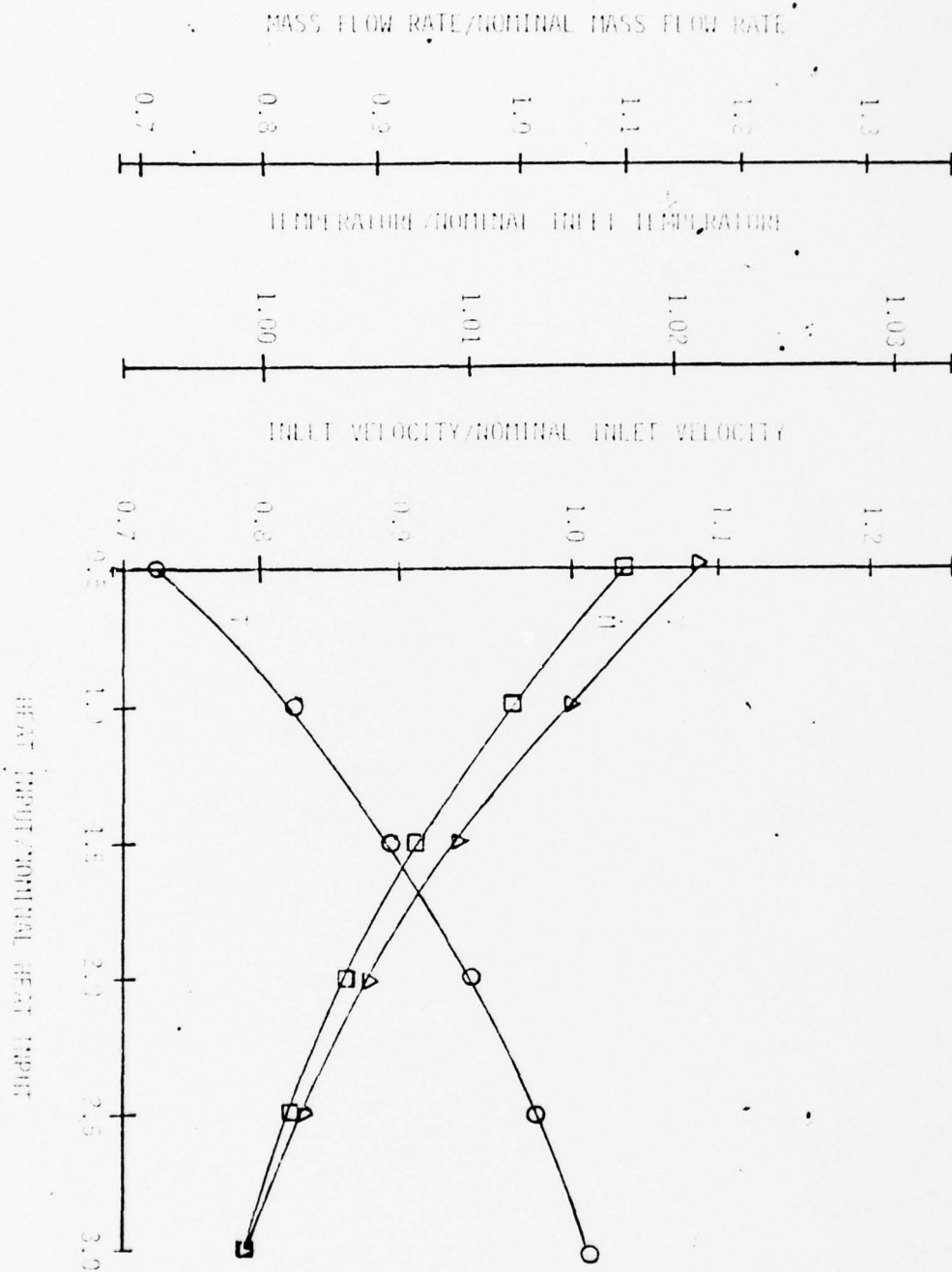
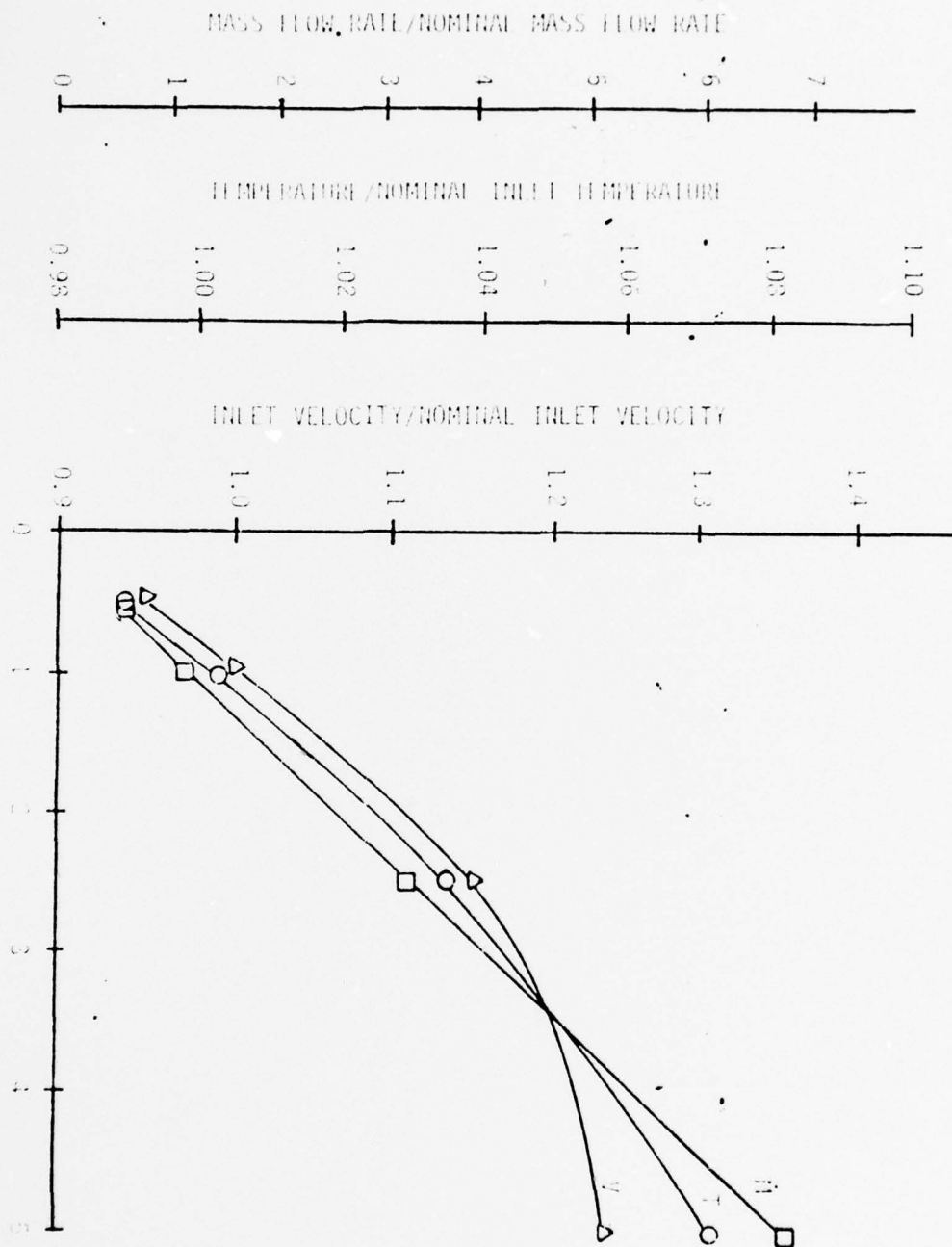
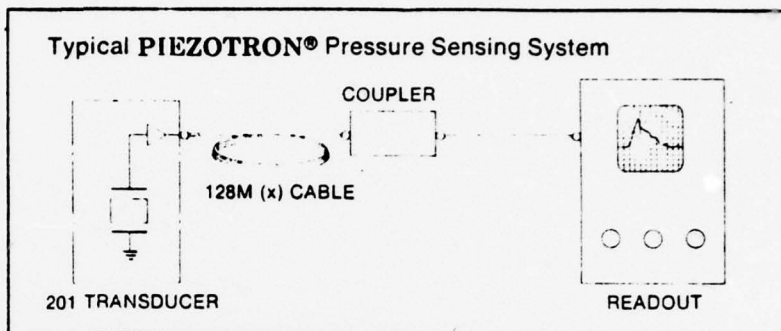


Figure 9. Variation in Inlet Velocity, Temperature, and Mass Flow Rate Versus Heating Values.



## APPENDIX A

### 201 SERIES MINI-GAGE



#### Couplers

To complete the system a wide choice of couplers is offered in the 548 and 549 series. Optional filters and several types of power inputs are available. Model 587D Coupler provides increased capability. Please refer to our Coupler Data Sheet for details.

In addition Models 583, 503D and 504D Laboratory Amplifiers are offered with extensive versatility and many options for more complete pressure studies.

#### Specifications

##### PERFORMANCE

	UNITS	201B1	201B2	201B4	201B5
Pressure Range, 5V out	psi	5,000	500	200	100
Overrange	psi	7,500	750	300	150
Resolution (noise)	psi rms	0.05	0.005	0.002	0.001
Maximum Pressure	psi	15,000	5,000	2,000	1,000
Sensitivity	mV/psi	1	10	25	50
Linearity, B.F.S.L.	%	+1	±1	±1	±1
Resonant Frequency, nom.	kHz	500	500	500	250
Rise Time, 10-90%	μ sec	1	1	1	2
Time Constant, R.T.	sec	1,500	400	200	100
Low Frequency Response, -5%	Hz	0.0003	0.001	0.0025	0.005
High Frequency Response, +5%	Hz	100,000	100,000	100,000	50,000

##### ENVIRONMENTAL

	UNITS	201B1	201B2	201B4	201B5
Vibration Sensitivity, max.	psi/g	0.002	0.002	0.002	0.002
Shock, 1 ms	g	5,000	5,000	5,000	5,000
Vibration Limit	g	500	500	500	500
Temperature Range	°F	-65 to 280	-65 to 280	-65 to 280	-65 to 280
Temperature Sensitivity Shift	/ F	0.03%	0.03%	0.03%	0.03%

##### ELECTRICAL

	UNITS	201B1	201B2	201B4	201B5
Output Current, min.	mA	2	2	2	2
Polarity, pressure increase		Negative	Negative	Negative	Negative
Bias Voltage	V	11 ±2	11 ±2	11 ±2	11 ±2
Circuit Return		Case	Case	Case	Case
Output Impedance, max.	ohms	100	100	100	100

##### MECHANICAL

	UNITS	201B1	201B2	201B4	201B5
Weight	gms	< 10	< 10	< 10	< 10
Case and Diaphragm Material		Stainless St.	Stainless St.	Stainless St.	Stainless St.
Mounting Torque	in-lb	24	24	24	24
Sealing		All Welded	All Welded	All Welded	All Welded

##### POWER SUPPLY

	UNITS	201B1	201B2	201B4	201B5
Constant Current Source	mA	4 ±1	4 ±1	4 ±1	4 ±1
Supply Ripple, max.	mV rms	25	25	25	25
Supply Voltage, no load	VDC	20-30	20-30	20-30	20-30
Source Impedance, nom.	ohms	250 k	250 k	250 k	250 k

APPENDIX B



Reference Number	Date of Test	Blower Status	Muffler Location	Pressure	Temperature	Velocity	Energy of Pulse, J
5381	6/26/78	Off	2	1,6,5A	7	-	33.80
5382	"	Off	"	1,6,5.5	7	-	106.4045
5400		Off	"	1,6,5A	7	-	56.59535
5402		Off	"	1,6,5A	1	-	49.01
5403		On	"	1,6,5A	1	-	34.06202
5408	7/11/78	On	"	1,5A,6	1	-	71.70709
5410	"	Off	"	1,5.5,6	2	-	64.22
5411	"	On	"	1,6,5.5	2	-	72.67
5412	"	Off	"	1,6,5.5	2	-	67.6
5413	"	Off	"	1,6,5.5	7	-	67.6
5414	"	Off	"	1,6,5.5	3	-	60.84
5415	"	On	"	1,6,5.5	3	-	57.46
5416	"	On	"	1,6,5.5	3	-	72.67
5420	"	Off	"	1,6,5A	7	-	23.66
5421	"	Off	"	1,6,5A	7	-	57.46
5422	"	On	"	1,6,5A	7	-	60.84
5423	"	On	"	6,5A,4	7	-	60.84
5424	"		"	1,6,5.5	3	-	64.22
5425	"	Off	"	1,6,5	5	-	62.53
5426	"	On	"	1,6,5	5	-	64.22
5427	"	Off	-	1,6,5	5	-	62.53
5428	"	On	-	1,6,5	5	-	67.60
5430	"	On	-	1,6,5	5	-	37.18
5431	"	Off	-	1,6,5	4	-	54.08
5433	"	On	-	1,6,5	4	-	59.15
5435	"	Off	-	1,6,5.5	3	-	59.15
5436	"	On	-	1,6,5.5	3	-	65.91
5437	"	On	-	1,6,5.5	3	-	65.91
5438	"	Off	-	1,6,5	2	-	60.84*
5439	"	On	-	1,6,5	2	-	64.22*
5441	"	On	-	1,6,5	2	-	72.67*
5443	"	Off	-	1,6,5	1	-	67.60*

Reference Number	Date of Test	Blower Status	Muffler Location	Pressure	Temperature	Velocity	Energy of Pulse, J
5444	7/11/78		-	1,6,5	1	-	77.74*
5445	"	On	-	1,6,5	1	-	77.74*
5446	"	On	-	1,6,5	1	-	67.60*
5448	7/12/78	On	2	1,5,6	1	-	60.84
5449	"	Off	2	1,6,5	2	-	55.77
5450	"	Off	-	1,5,6	2	-	64.22
5451	"	On	-	1,5,6	2	-	59.15
5452	"	Off	-	1,5,6	3	-	64.22
5453	"	On	-	1,5,6	3	-	67.60
5454	"	On	-	1,5,6	3	-	74.93643
5456	"	Off	-	1,5,6	4	-	67.60
5457	"	On	-	1,5,6	4	-	64.22
5459	"	On	1,2	1,5,6	4	-	72.67
5460	"	Off	"	4,6,5	5	-	60.84*
5461	"	Off	"	4,6,5	5	-	62.53*
5462	"	On	"	4,6,5	4	-	64.22*
5463	"	On	"	4,6,5	5	-	57.46
5464	"	Off	"	4,6,5	6	-	57.46
5466	"	On	"	4,6,5	6	-	57.46
5467	"	On	"	4,6,5	6	-	57.46
5468	"	Off	"	4,6,5	1	-	60.84
5469	"	On	"	4,6,5	1	-	60.84
5470	"	On	"	1,6,5A	1	-	55.77
5471	"	On	"	4,6,5	1	-	64.22
5472	"	On	"	4,6,5	1	-	67.60
5473	"		1	4,6,5	1	-	60.84
5474	"		1	4,6,5	1	-	67.60
5475	"	On	1	4,6,5	1	-	62.53
5476	"	On	1	4,6,5	1	-	64.22
5477	"		1	4,6,5	2	-	46.475
5478	"	On	1	4,6,5	2	-	60.84
5479	"	On	1	4,6,5	2	-	59.15

Reference Number	Date of Test	Blower Status	Muffler Location	Pressure	Temperature	Velocity	Energy of Pulse, J
5480	7/12/78	Off	1	4,6,5	3	-	59.15
5481	"	Off	1	4,6,5	3	-	55.77
5482	"	On	1	4,6,5	3	-	59.15
5483	"	On	1	4,6,5	3	-	66.755
5484	"	On	1	4,6,5	4	-	65.91
5485	"		1	4,6,5	5	-	60.84
5486	"	Off	1	4,6,5	5	-	64.22
5491	"	Off	1	4,6,5	4	-	62.53
5492	"	On	1	4,6,5	4	-	54.08
5493	"		1	4,7,5	7	-	64.22
5494	"	On	1	4,7,5	7	-	64.22
5496	"	Off	1	4,7,5	7	-	33.80
5497	"	Off	1	4,7,5	7	-	54.08
5498	"	Off	1	4,7,5	7	-	50.70
5500	"	Off	1	4,7,5	4	-	54.08
5501	"	Off	1	4,7,5	4	-	54.08
5502	"	On	1	4,7,5	4	-	62.53
5503	"	On	1	4,7,5	4	-	69.29
5504	"	On	1	4,7,5	4	-	70.135
5505	"	On	1	4,7,5	5	-	67.60
5506	"	On	1	4,7,5	5	-	65.065
5507	"	On	1	4,7,5	5	-	70.135
5508	"	Off	1	4,7,5	5	-	65.91
5509	"	Off	1	4,7,5	5	-	54.08
5512	"	On	1	4,7,5	4	-	64.22
5517	7/14/78	On	1	4,5	4	1	65.065
5518	"	On	1	4,5	5	1	55.77
5519	"	On	1	4,5	5	4	87.035
5521	"	On	1	4,5	5	4	67.60
5522	"	On	1	4,5	5	4	80.275
5523	"	On	1	4,5	4	5	67.60

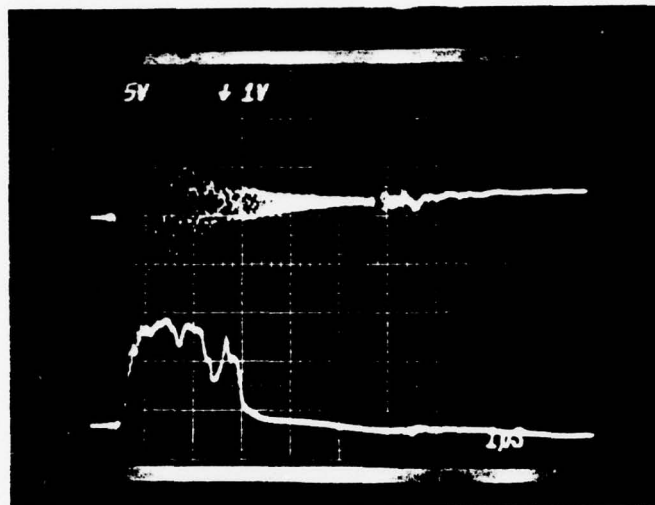
\* Assumed Value

PVC Circulator Experimental Data

Page 135

No. 5381

Date 26 June 1978



Gun Data

1. Upper Trace

Voltage 1μsec/div

Time Scale 1V/div

Inverted? Yes No

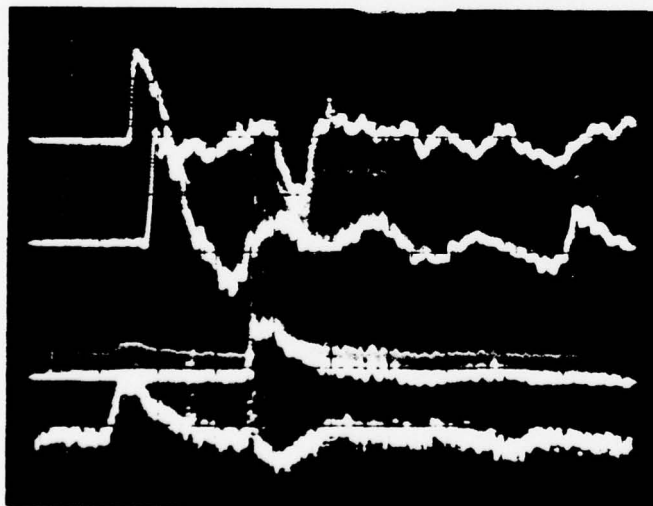
2. Lower Trace

Voltage 5V/div

Time Scale 1μsec/div

Inverted? Yes No

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5A</sub> Ch. 3 0.02V/div

T<sub>7</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.9kV

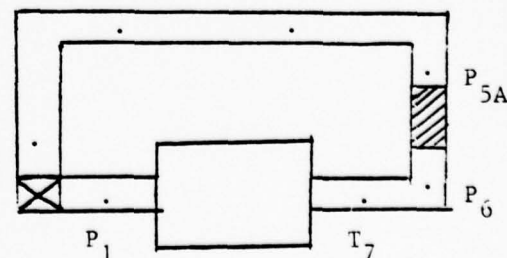
Flow? On Off

Gas Type N<sub>2</sub>

Notes: 1 muffler only

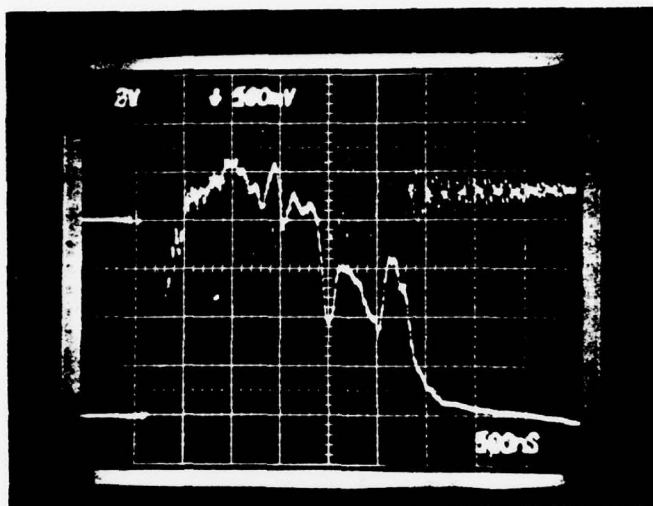
Analyzed Data:

E = 33.80



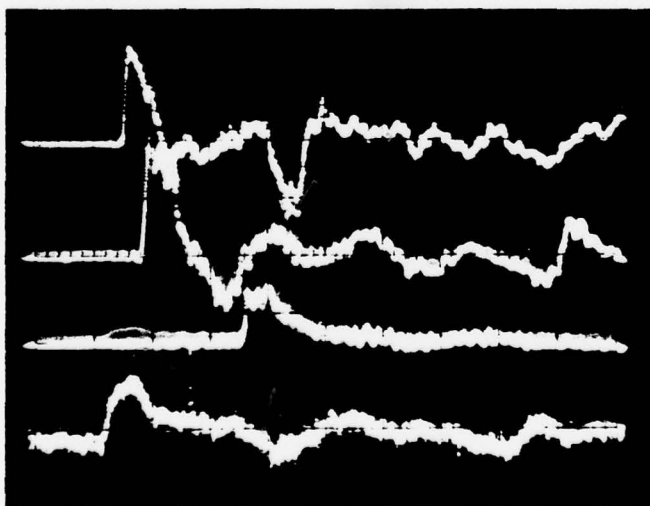
PVC Circulator Experimental Data

Page 136  
 No. 5382  
 Date 26 June 1978



Gun Data

1. Upper Trace  
 Voltage 500mV/div  
 Time Scale 500nsec/div  
 Inverted? (Yes) No
2. Lower Trace  
 Voltage 2V/div  
 Time Scale 500nsec/div  
 Inverted? Yes (No)  
 Attenuation \_\_\_\_\_

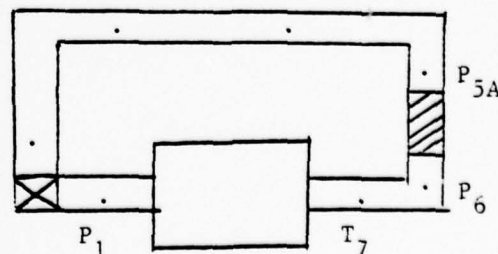


Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
 P<sub>6</sub> Ch. 2 0.02V/div  
 P<sub>5.5</sub> Ch. 3 0.02V/div  
 T<sub>7</sub> Ch. 4 0.05V/div  
 Time Scale 2msec/div  
 Sustainer Voltage 26.2kV  
 Flow? On (Off)  
 Gas Type N<sub>2</sub>  
 Notes: \_\_\_\_\_

Analyzed Data:

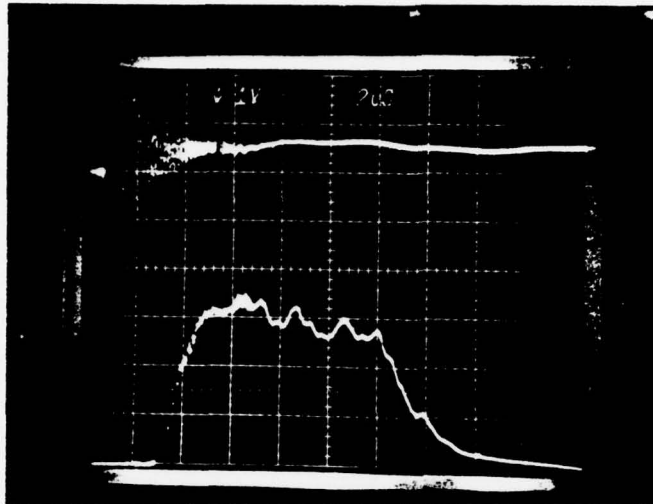
$$E = 106.4045$$





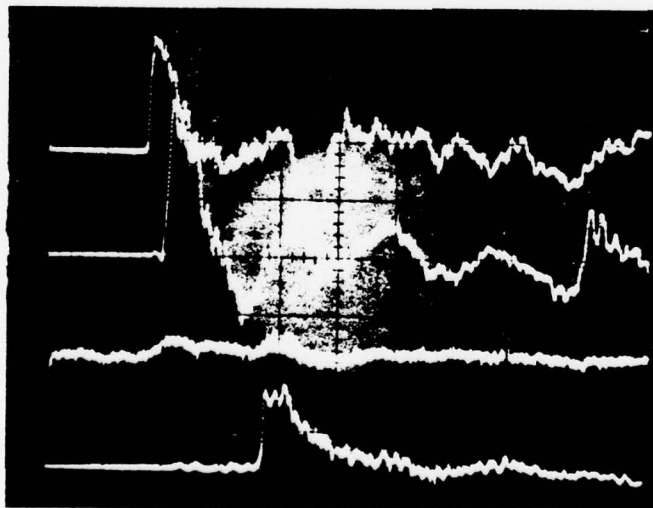
PVC Circulator Experimental Data

Page 137  
No. 5400  
Date \_\_\_\_\_



Gun Data

1. Upper Trace  
Voltage 1V /div  
Time Scale 2uS/div  
Inverted? Yes No
2. Lower Trace  
Voltage 5V /div  
Time Scale 500nS/div  
Inverted? Yes No  
Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V /div

P<sub>6</sub> Ch. 2 0.02V /div

T<sub>7</sub> Ch. 3 0.10V /div

P<sub>5A</sub> Ch. 4 0.02V /div

Time Scale 2mS /div

Sustainer Voltage 28.8kV

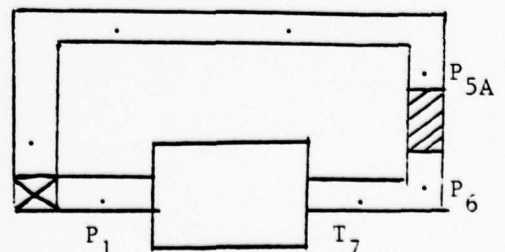
Flow? On Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 56.59535$$

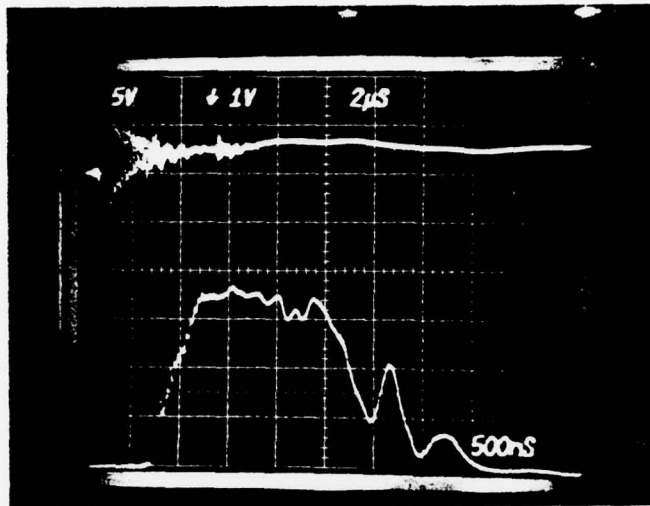


# PVC Circulator Experimental Data

Page 138

No. 5402

Date \_\_\_\_\_



## Gun Data

### 1. Upper Trace

Voltage 1V /div

Time Scale 2μsec/div

Inverted? Yes No

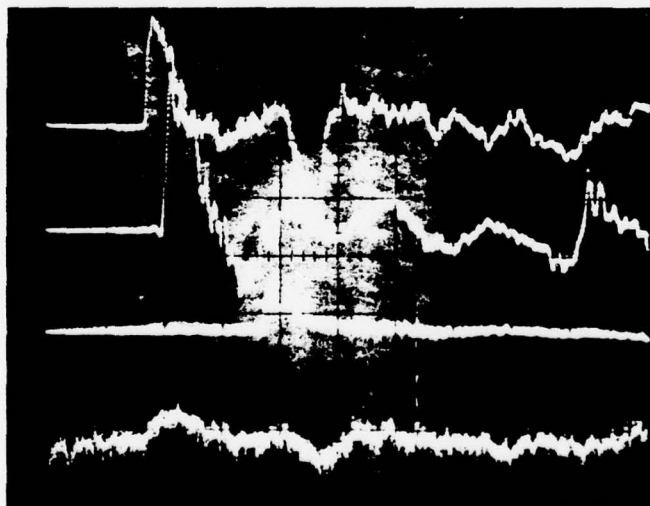
### 2. Lower Trace

Voltage 5V /div

Time Scale 500nsec/div

Inverted? Yes No

Attenuation \_\_\_\_\_



## Voltages

P<sub>1</sub> Ch. 1 0.02V /div

P<sub>6</sub> Ch. 2 0.02V /div

P<sub>5A</sub> Ch. 3 0.05V /div

T<sub>1</sub> Ch. 4 0.05V /div

Time Scale 2msec /div

Sustainer Voltage 25.9kV

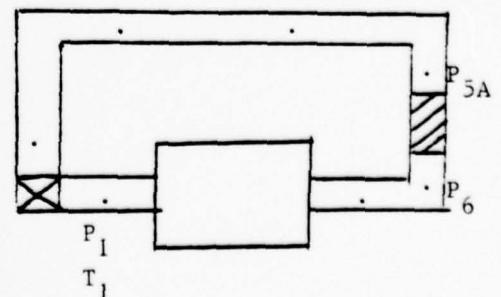
Flow? On Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 49.01$$

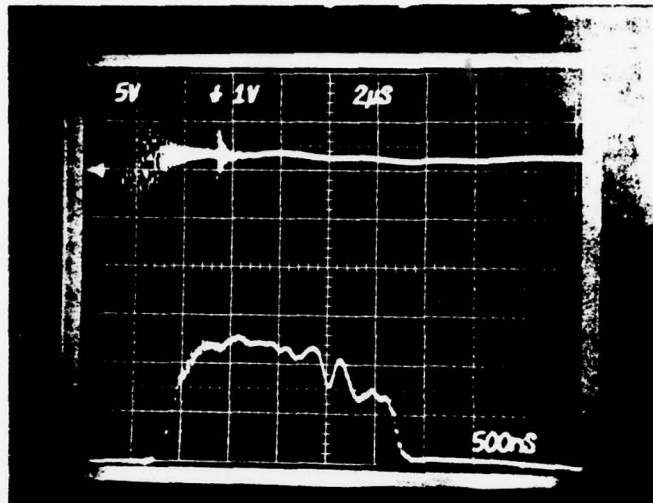


# PVC Circulator Experimental Data

Page 139

No. 5403

Date \_\_\_\_\_



## Gun Data

### 1. Upper Trace

Voltage 1V /div

Time Scale 2μsec /div

Inverted? (Yes) No

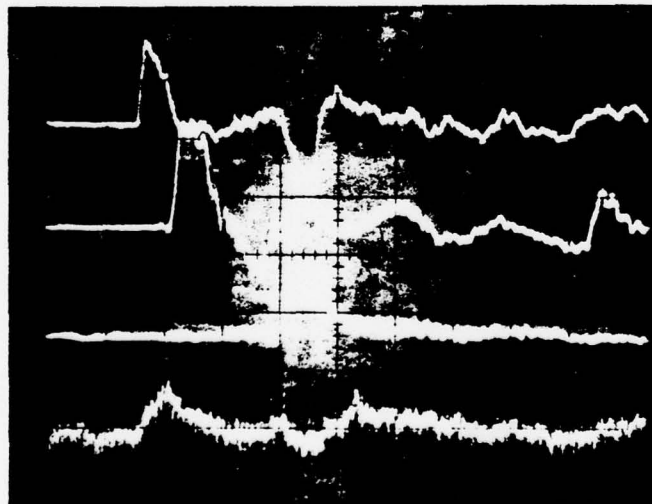
### 2. Lower Trace

Voltage 5V /div

Time Scale 500nsec /div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



## Voltages

$P_1$  Ch. 1 0.02V /div

$P_6$  Ch. 2 0.02V /div

$P_{5A}$  Ch. 3 0.02V /div

$T_1$  Ch. 4 0.05V /div

Time Scale 2msec /div

Sustainer Voltage 26.0kV

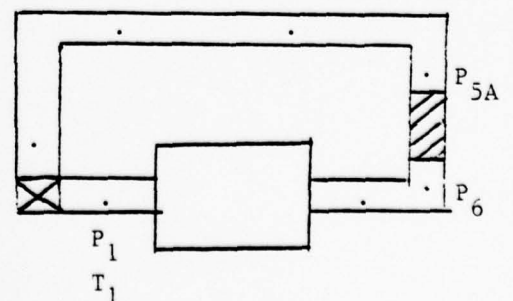
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 34.06202$$

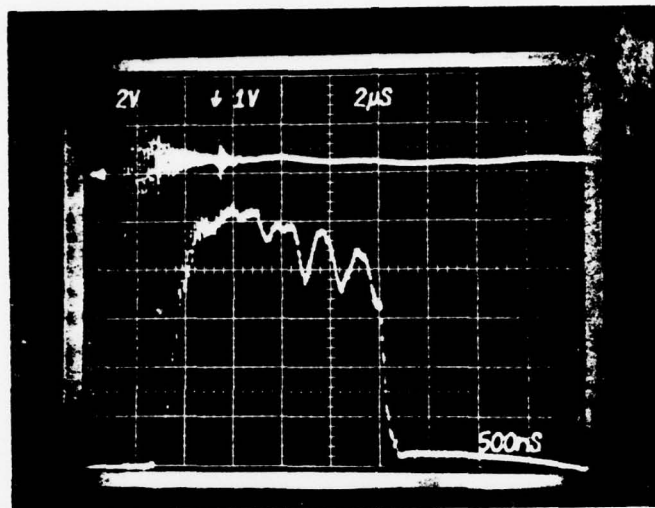


# PVC Circulator Experimental Data

Page 140

No. 5408

Date 11 July 1978



## Gun Data

### 1. Upper Trace

Voltage 1V /div

Time Scale 2μsec /div

Inverted? (Yes) No

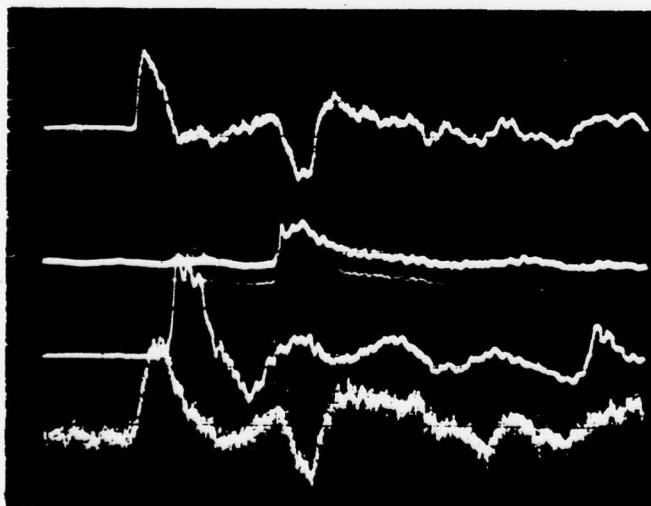
### 2. Lower Trace

Voltage 2V /div

Time Scale 500nsec /div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



## Voltages

P<sub>1</sub> Ch. 1 0.02V /div

P<sub>5A</sub> Ch. 2 0.02V /div

P<sub>6</sub> Ch. 3 0.02V /div

T<sub>1</sub> Ch. 4 0.05V /div

Time Scale 2msec /div

Sustainer Voltage 26.7kV

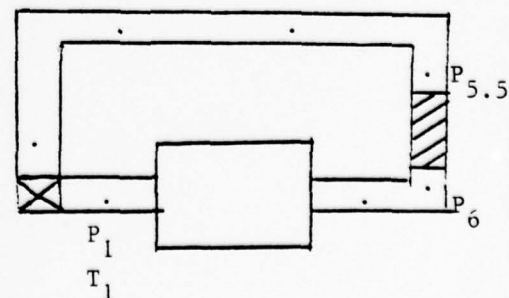
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 71.70709$$

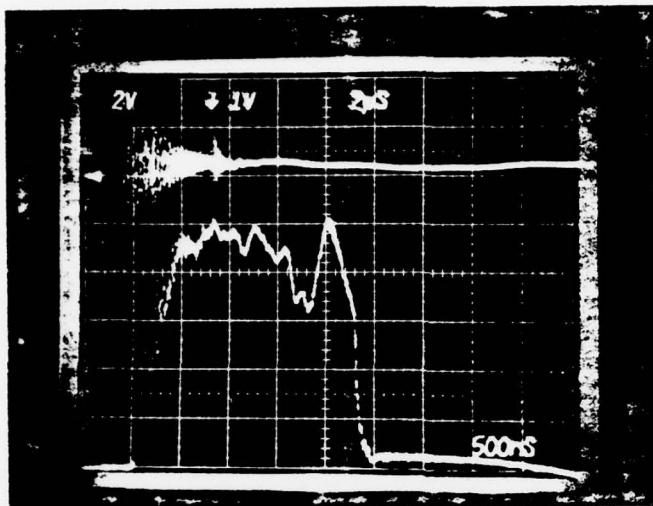


PVC Circulator Experimental Data

Page 141

No. 5410

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 1V/div

Time Scale 2μsec/div

Inverted? (Yes) No

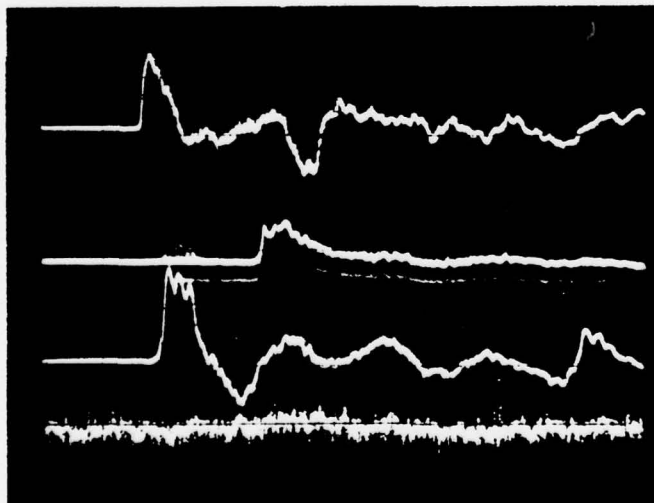
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>5.5</sub> Ch. 2 0.02V/div

P<sub>6</sub> Ch. 3 0.02V/div

T<sub>2</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.3kV

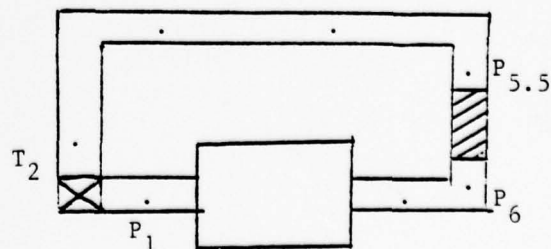
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 64.22$$



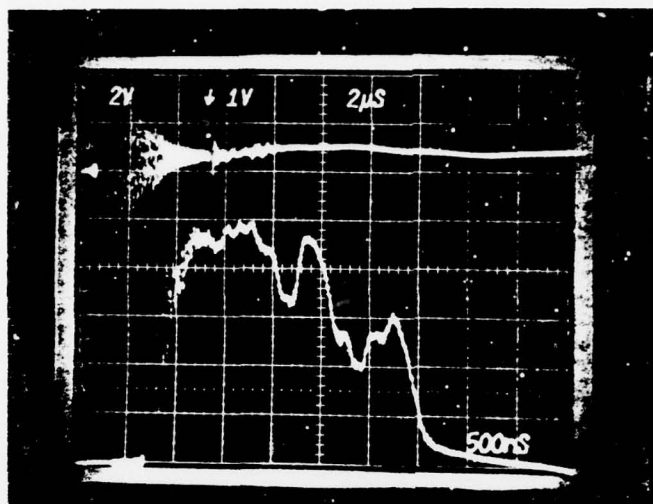


PVC Circulator Experimental Data

Page 143

No. 5412

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 1V /div

Time Scale 2μsec /div

Inverted? (Yes) No

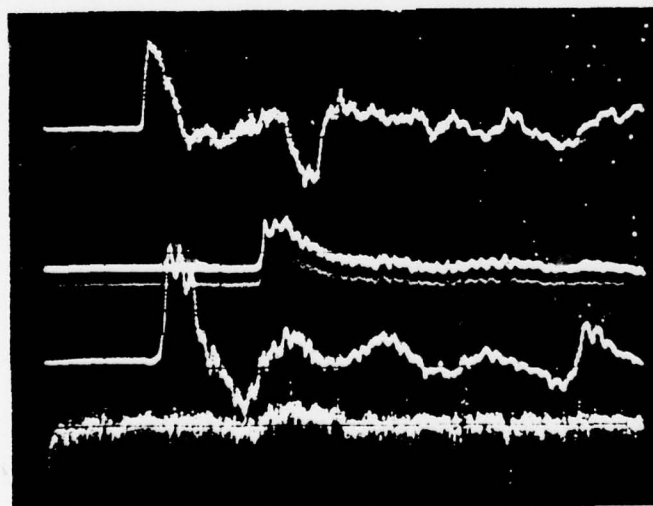
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec /div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V /div

P<sub>6</sub> Ch. 2 0.02V /div

P<sub>5.5</sub> Ch. 3 0.02V /div

T<sub>2</sub> Ch. 4 0.05V /div

Time Scale 2msec /div

Sustainer Voltage 25.8

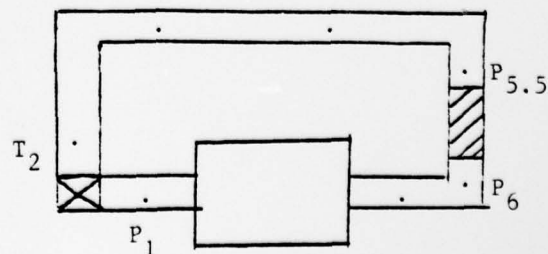
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 67.6$$

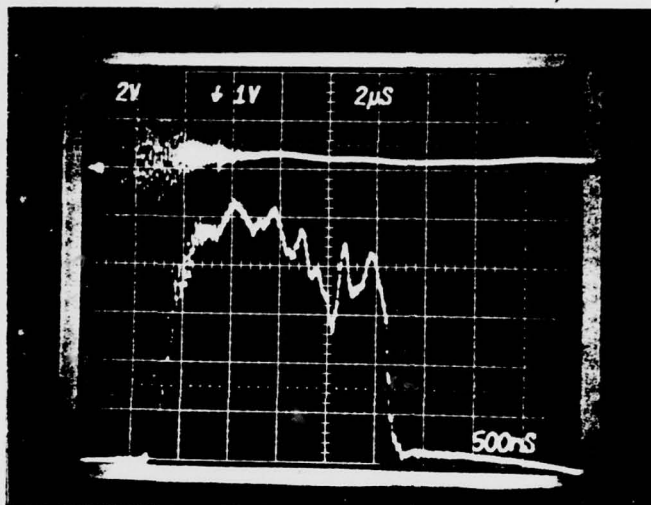


PVC Circulator Experimental Data

Page 144

No. 5413

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 1V /div

Time Scale 2μsec /div

Inverted? (Yes) No

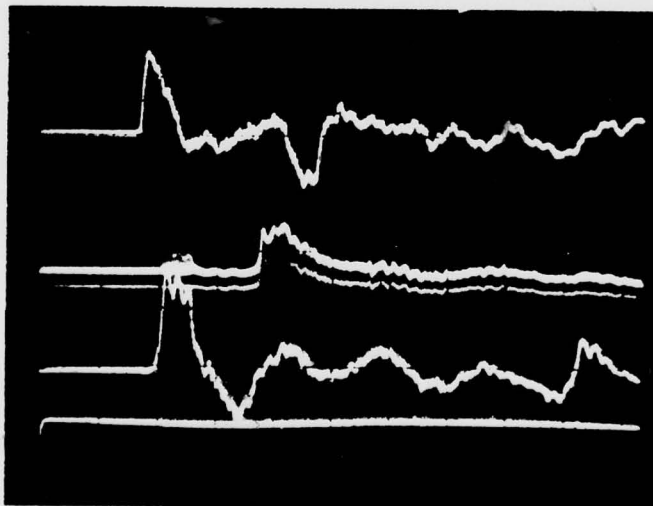
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec /div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V /div

P<sub>6</sub> Ch. 2 0.02V /div

P<sub>5.5</sub> Ch. 3 0.02V /div

T<sub>7</sub> Ch. 4 0.05V /div

Time Scale 2msec /div

Sustainer Voltage 25.8

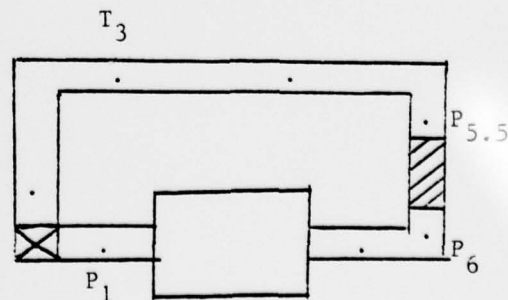
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: temp. unit off

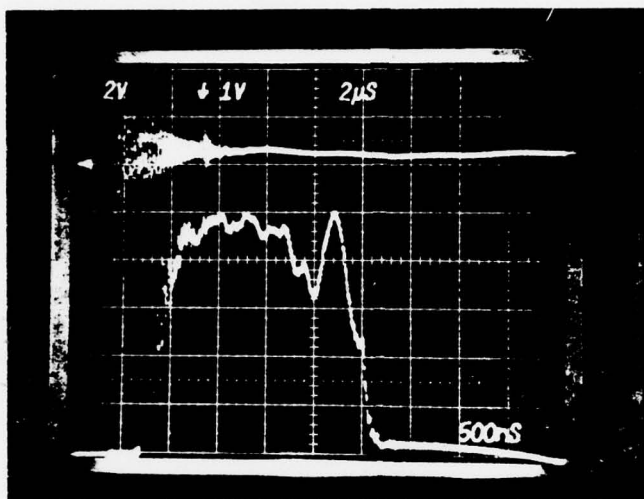
Analyzed Data:

E = 67.6



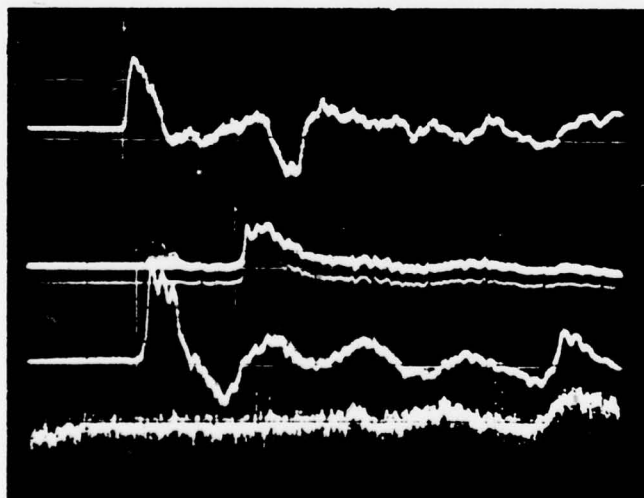
PVC Circulator Experimental Data

Page 145  
No. 5414  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 1V/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



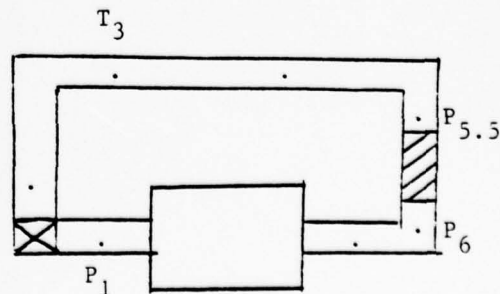
Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5.5</sub> Ch. 3 0.02V/div  
T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 2msec/div  
Sustainer Voltage 25.8  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

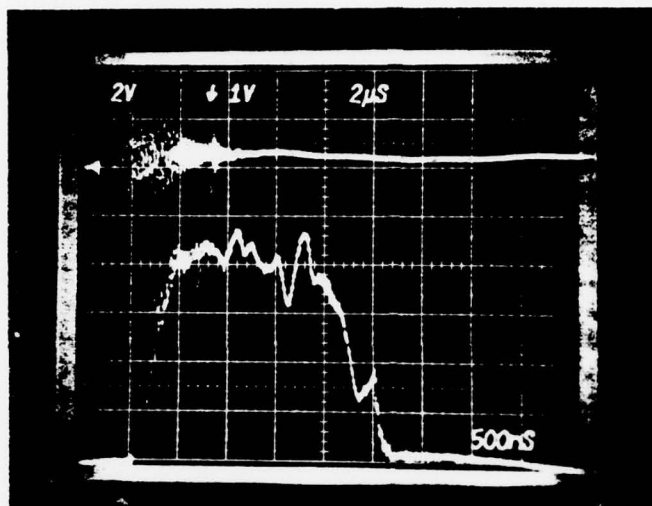
Analyzed Data:

$$E = 60.84$$



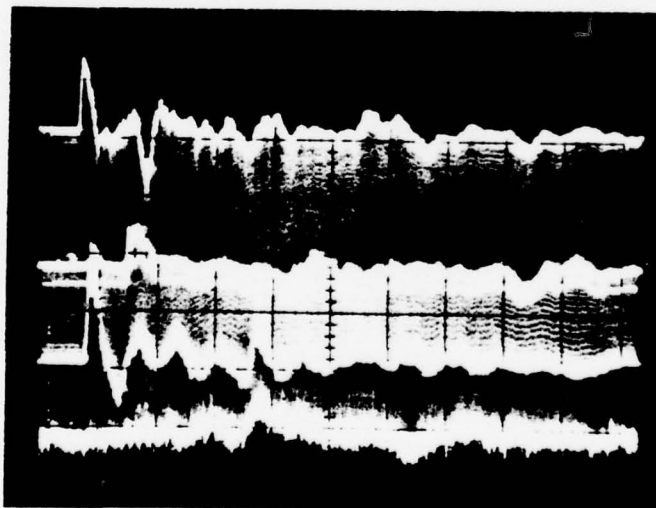
# PVC Circulator Experimental Data

Page 146  
No. 5415  
Date 11 July 1978



## Gun Data

1. Upper Trace  
Voltage 1V/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



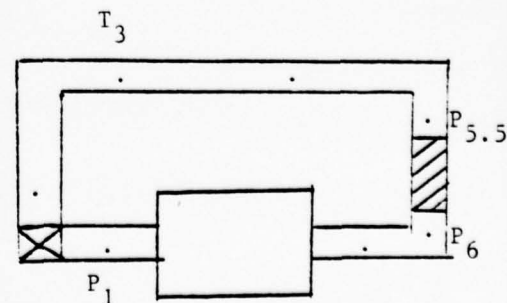
## Voltages

- $P_1$  Ch. 1 0.02V/div  
 $P_6$  Ch. 2 0.02V/div  
 $P_{5.5}$  Ch. 3 0.02V/div  
 $T_3$  Ch. 4 0.05V/div

Time Scale 5msec/div  
Sustainer Voltage 25.8  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

Analyzed Data:

$$E = 57.46$$

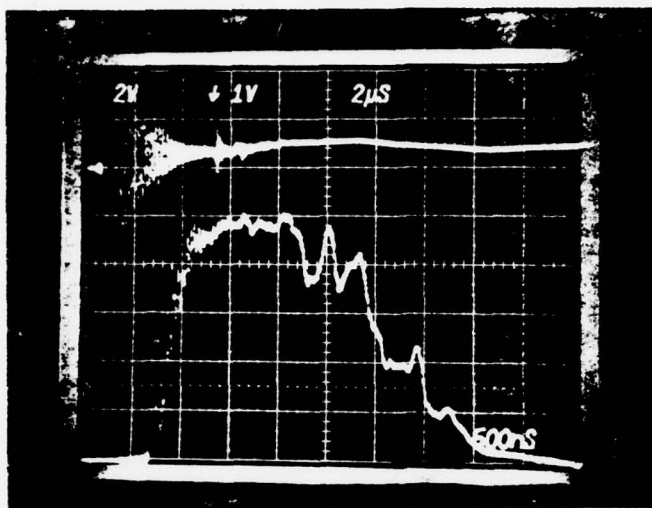


PVC Circulator Experimental Data

Page 147

No. 5416

Date 30 June 1978



Gun Data

1. Upper Trace

Voltage 1V /div

Time Scale 2μsec/div

Inverted? Yes No

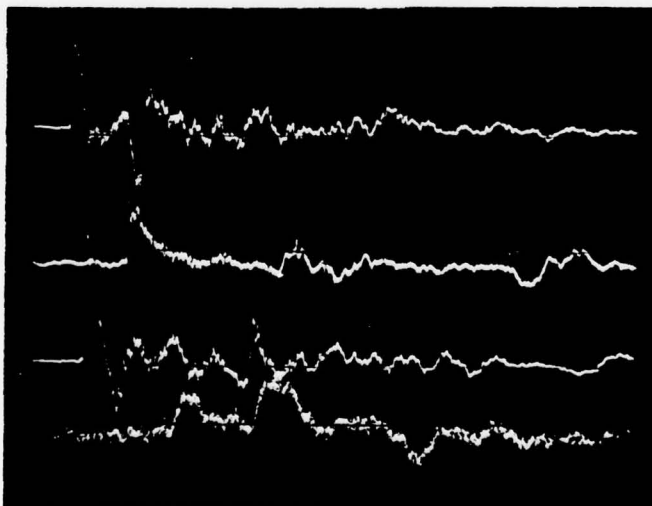
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes No

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V /div

P<sub>6</sub> Ch. 2 0.02V /div

P<sub>5.5</sub> Ch. 3 0.02V /div

T<sub>3</sub> Ch. 4 0.05V /div

Time Scale 5msec /div

Sustainer Voltage 25.8

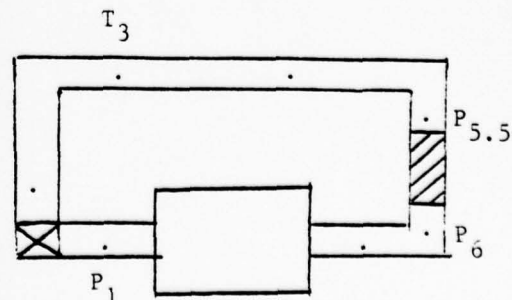
Flow? On Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 72.67$$



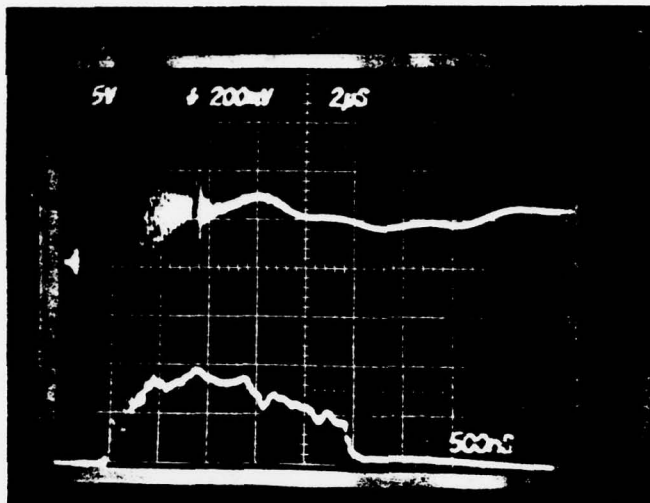


PVC Circulator Experimental Data

Page 148

No. 5420

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 200mV/div

Time Scale 2msec/div

Inverted? (Yes) No

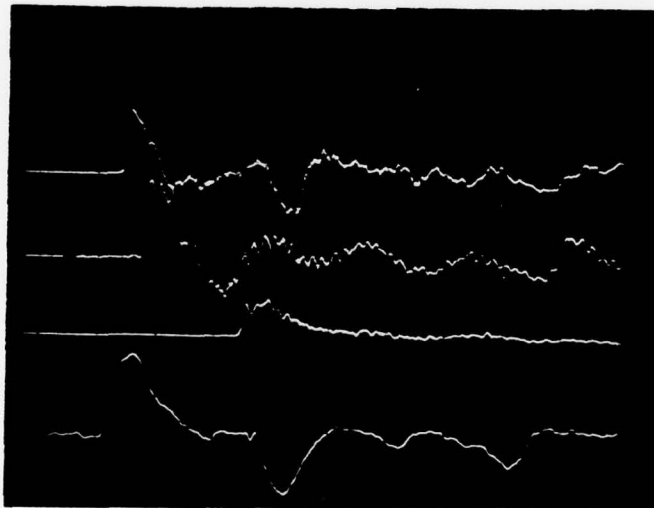
2. Lower Trace

Voltage 5V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5A</sub> Ch. 3 0.02V/div

T<sub>7</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

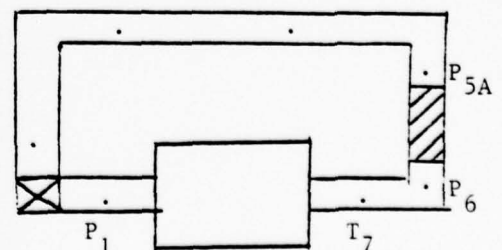
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: Muffler (11)

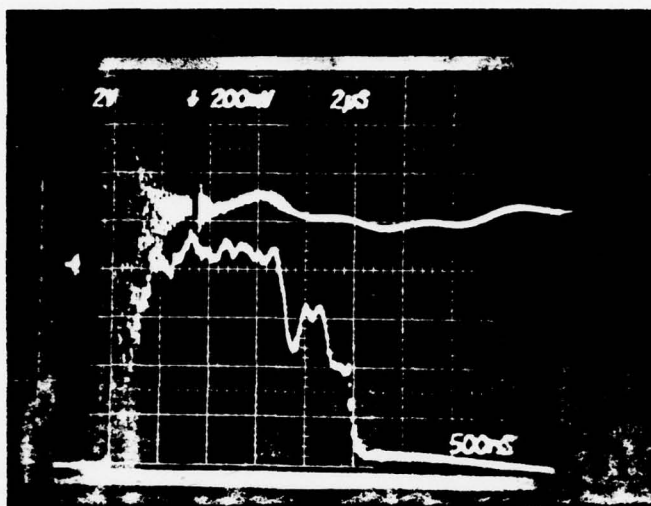
Analyzed Data:

$$E = 23.66$$



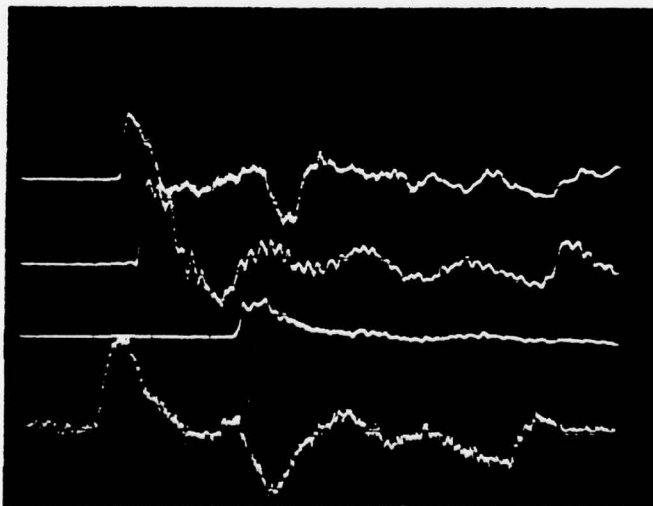
PVC Circulator Experimental Data

Page 149  
No. 5421  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2msec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5A</sub> Ch. 3 0.02V/div  
T<sub>7</sub> Ch. 4 0.05V/div

Time Scale 2msec/div  
Sustainer Voltage 25.8kV

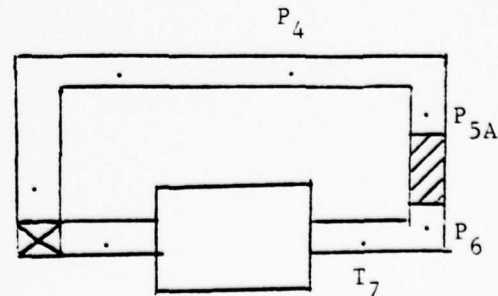
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 57.46$$

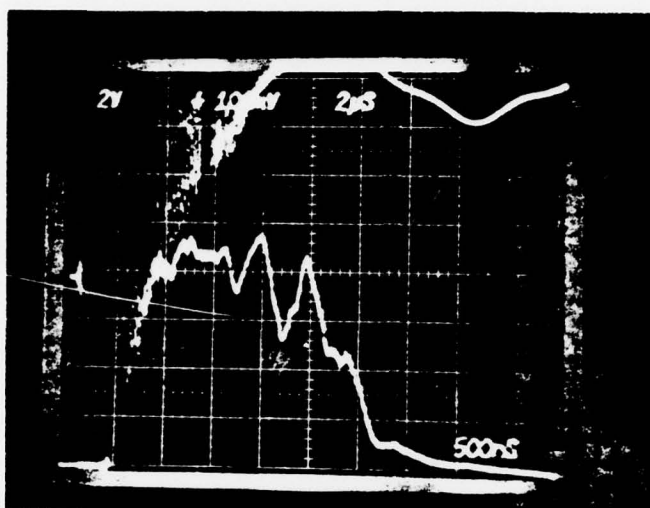


PVC Circulator Experimental Data

Page 150

No. 5422

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 2msec/div

Inverted? (Yes) No

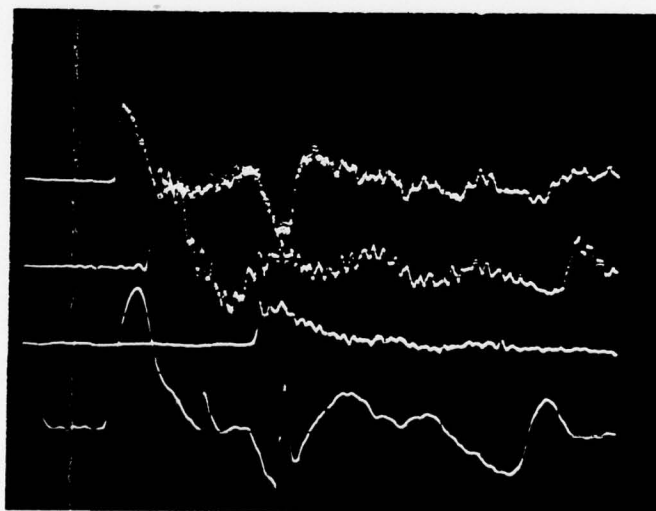
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5A</sub> Ch. 3 0.02V/div

T<sub>7</sub> Ch. 4 0.05V/div

Time Scale 2msec /div

Sustainer Voltage 25.8kV

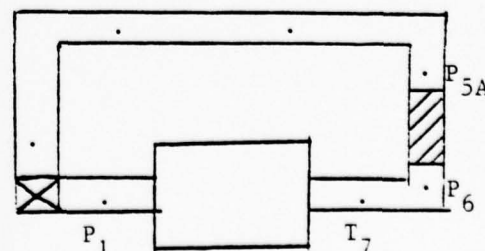
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: Muffler (II)

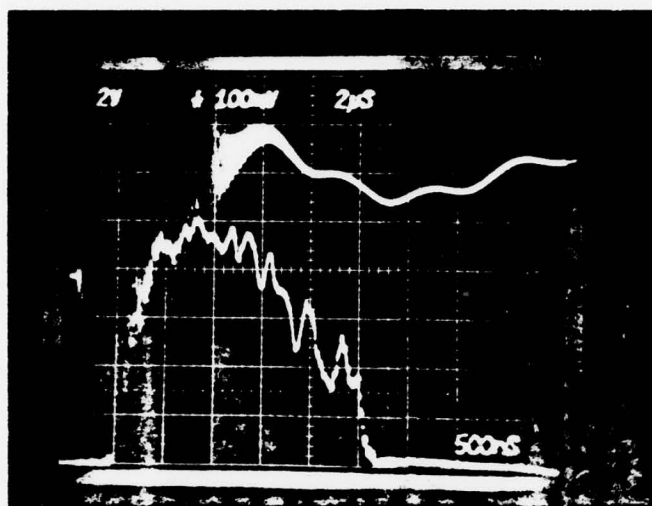
Analyzed Data:

$$E = 60.84$$



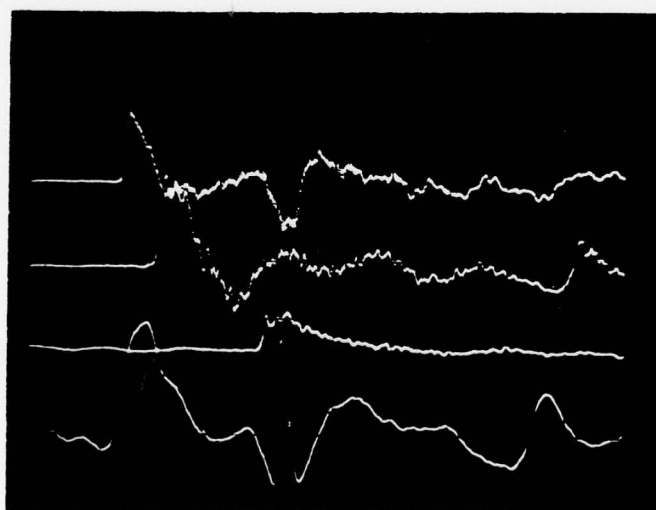
# PVC Circulator Experimental Data

Page 151  
No. 5423  
Date 11 July 1978



## Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 2msec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V /div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



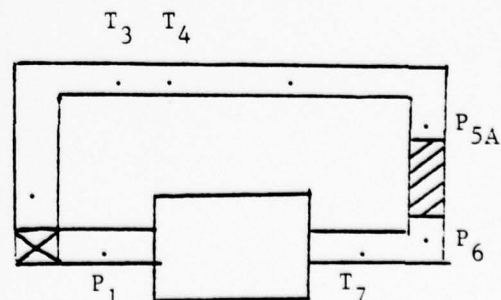
## Voltages

- P<sub>6</sub> Ch. 1 0.02V/div  
P<sub>5A</sub> Ch. 2 0.02V/div  
P<sub>4</sub> Ch. 3 0.02V/div  
T<sub>7</sub> Ch. 4 0.05V/div

Time Scale 2msec/div  
Sustainer Voltage 25.3kV  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: Muffler

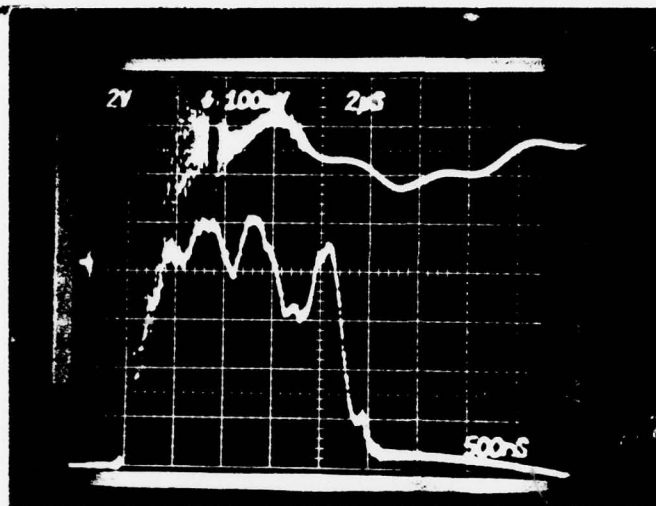
Analyzed Data:

$$E = 60.84$$



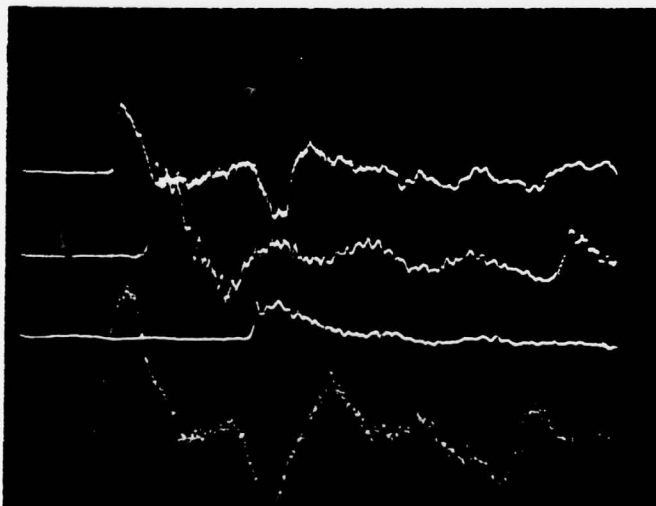
PVC Circulator Experimental Data

Page 152  
No. 5424  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



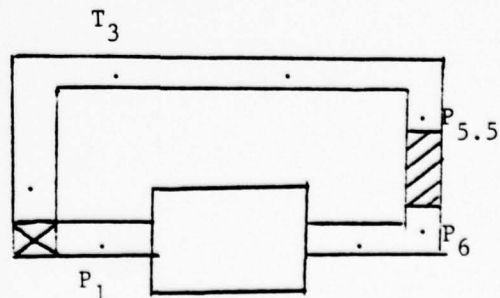
Voltages

P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5.5</sub> Ch. 3 0.02V/div  
T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 2msec/div  
Sustainer Voltage 25.8  
Flow? On Off  
Gas Type N<sub>2</sub>  
Notes: amp out

Analyzed Data:

$$E = 64.22$$



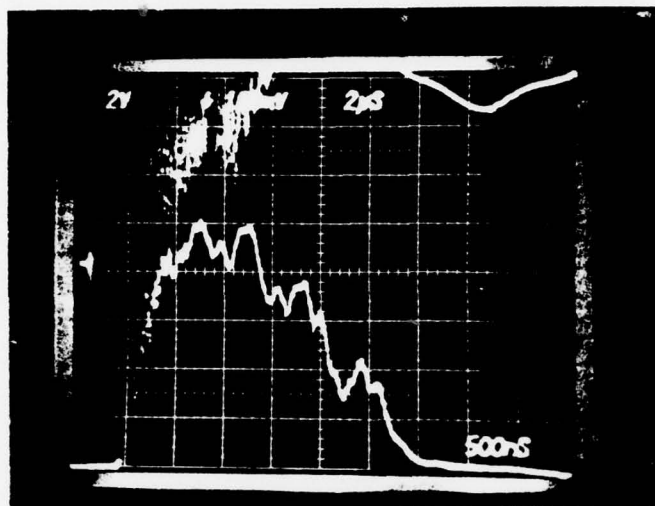


# PVC Circulator Experimental Data

Page 153

No. 5425

Date 11 July 1978



## Gun Data

### 1. Upper Trace

Voltage 100mV/div

Time Scale 2msec/div

Inverted? (Yes) No

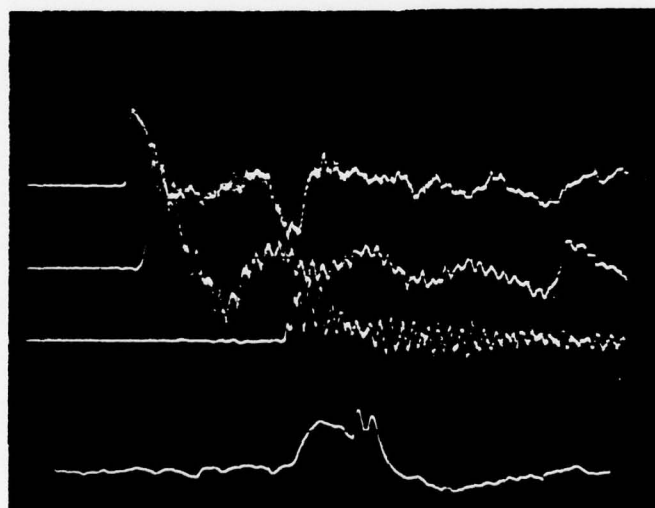
### 2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



## Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

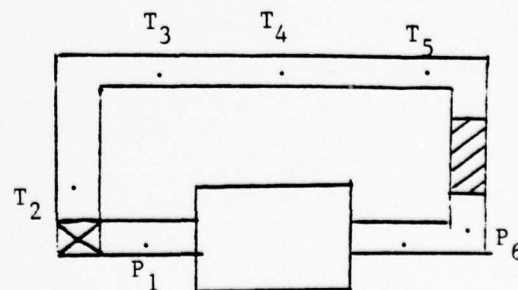
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: Muffler (II)

Analyzed Data:

$$E = 62.53$$

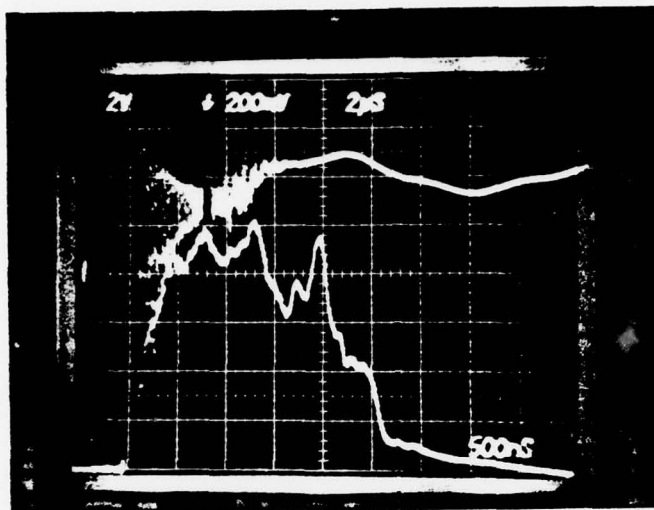


PVC Circulator Experimental Data

Page 154

No. 5426

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 200mV/div

Time Scale 2msec/div

Inverted? (Yes) No

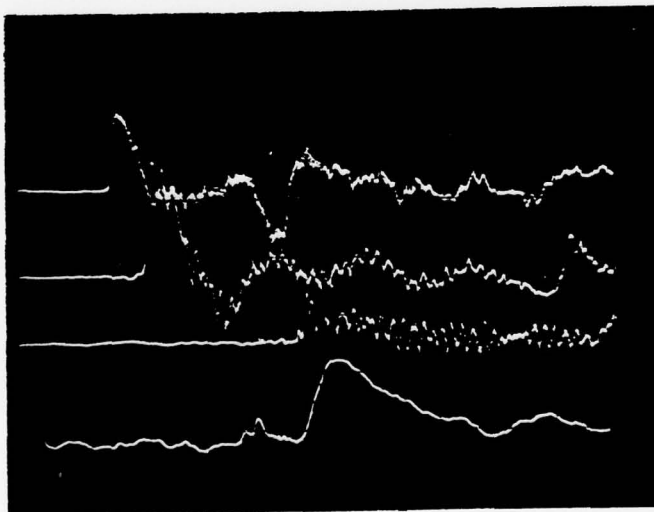
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V /div

P<sub>6</sub> Ch. 2 0.02V /div

P<sub>5</sub> Ch. 3 0.02V /div

T<sub>5</sub> Ch. 4 0.05V /div

Time Scale 2msec /div

Sustainer Voltage 25.8kV

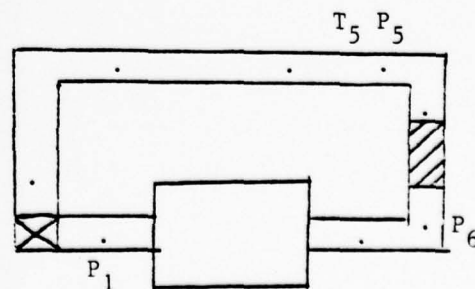
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 64.22$$

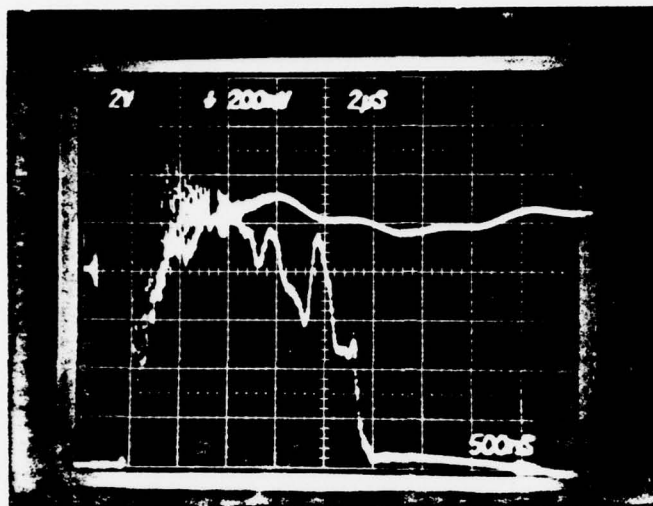


PVC Circulator Experimental Data

Page 155

No. 5427

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 200mV/div

Time Scale 2msec/div

Inverted? (Yes) No

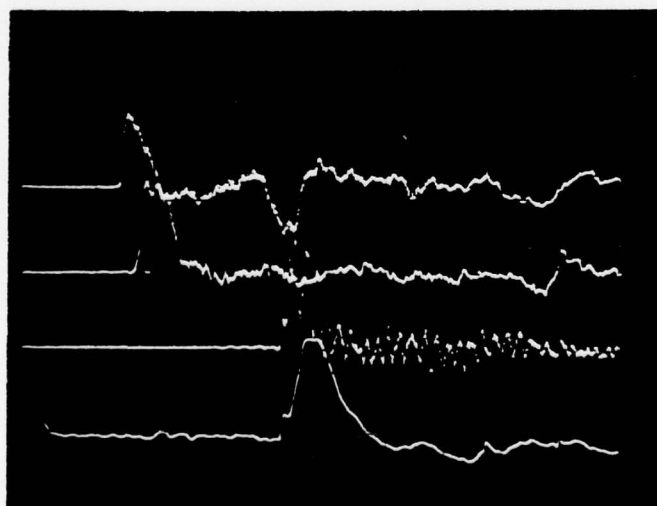
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

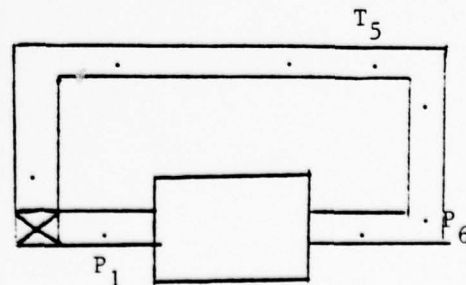
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: No Muffler

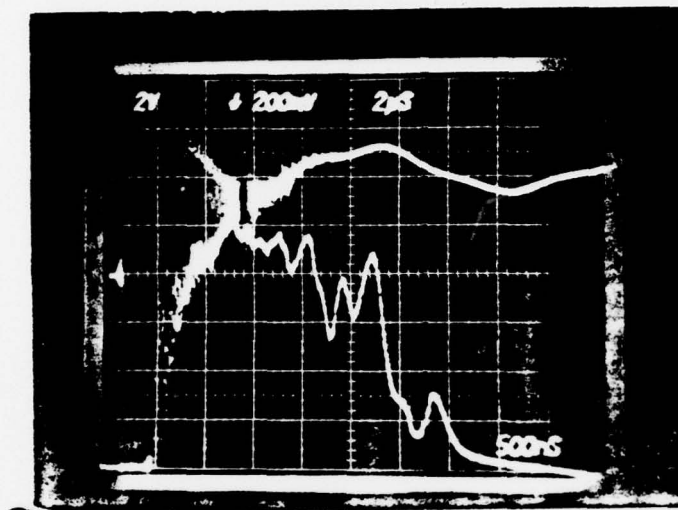
Analyzed Data:

$$E = 62.53$$



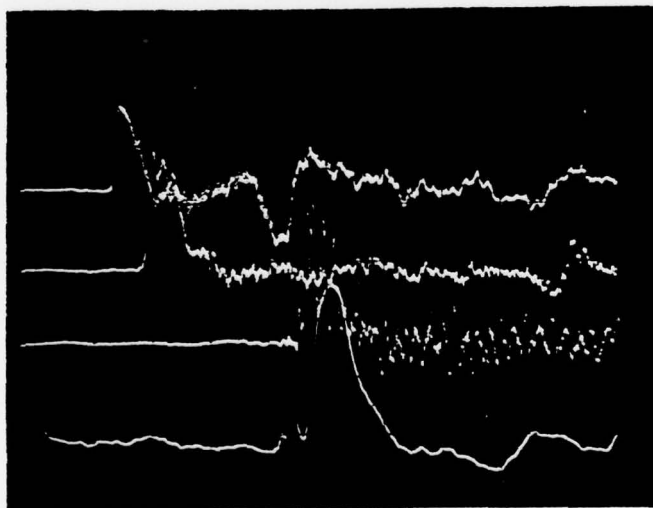
# PVC Circulator Experimental Data

Page 156  
No. 5428  
Date 11 July 1978



## Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2msec/div  
Inverted? ☒ Yes ☐ No
2. Lower Trace  
Voltage 2V /div  
Time Scale 500nsec/div  
Inverted? Yes ☐ No ☒  
Attenuation \_\_\_\_\_

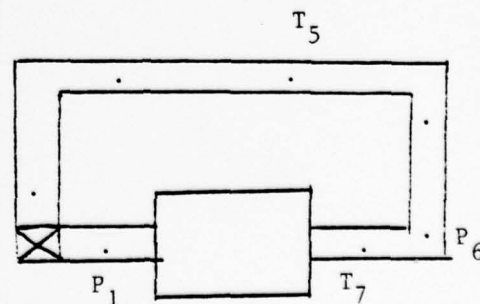


## Voltages

- P<sub>1</sub> Ch. 1 0.02V /div  
P<sub>6</sub> Ch. 2 0.02V /div  
P<sub>5</sub> Ch. 3 0.02V /div  
T<sub>5</sub> Ch. 4 0.05V /div  
Time Scale 2msec /div  
Sustainer Voltage 25.8kV  
Flow? ☒ On ☐ Off  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

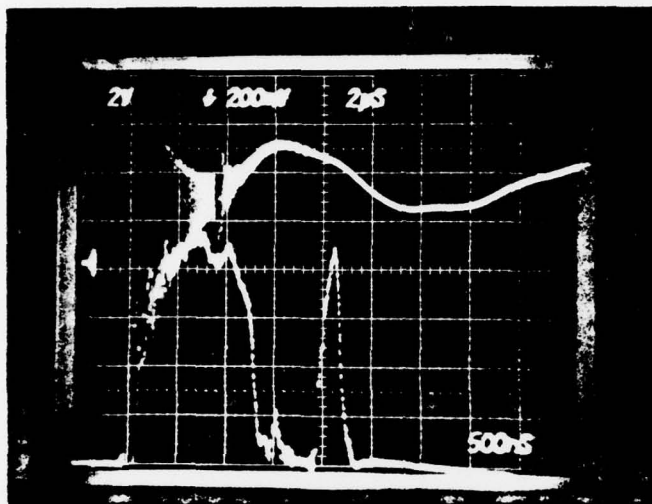
Analyzed Data:

$$E = 67.6$$



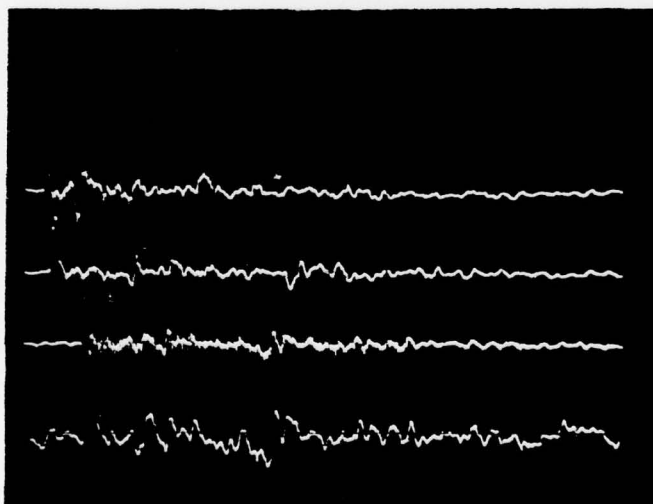
PVC Circulator Experimental Data

Page 157  
 No. 5430  
 Date 11 July 1978



Gun Data

1. Upper Trace  
 Voltage 200mV/div  
 Time Scale 2msec/div  
 Inverted? (Yes) No
2. Lower Trace  
 Voltage 2V /div  
 Time Scale 500nsec/div  
 Inverted? Yes (No)  
 Attenuation \_\_\_\_\_



Voltages

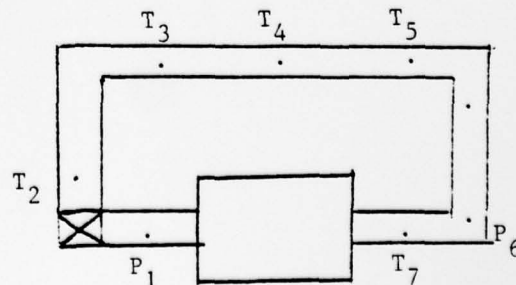
- P<sub>1</sub> Ch. 1 0.02V /div  
 P<sub>6</sub> Ch. 2 0.02V /div  
 P<sub>5</sub> Ch. 3 0.02V /div  
 T<sub>5</sub> Ch. 4 0.05V /div

Time Scale 10msec /div  
 Sustainer Voltage 25.8kV  
 Flow? (On) Off  
 Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

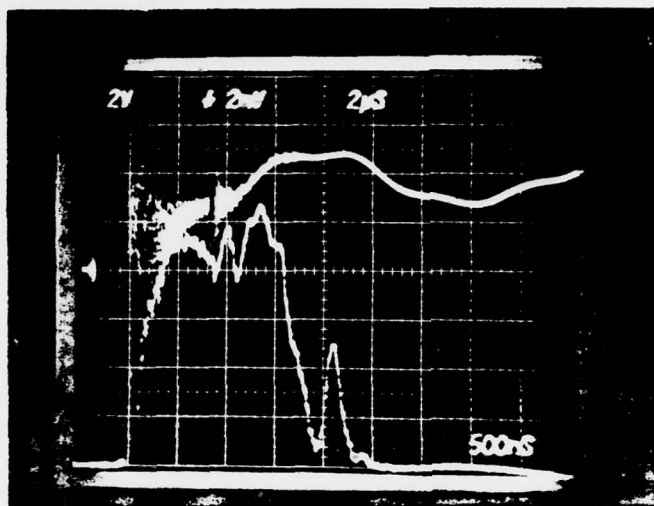
$$E = 37.18$$





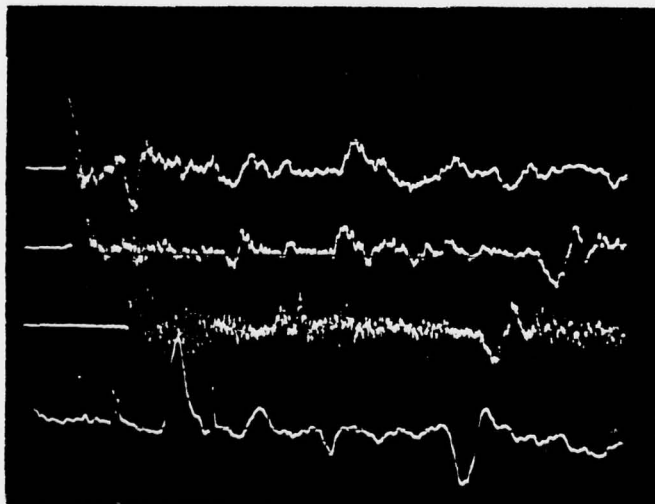
PVC Circulator Experimental Data

Page 158  
No. 5431  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 2mV/div  
Time Scale 2msec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_

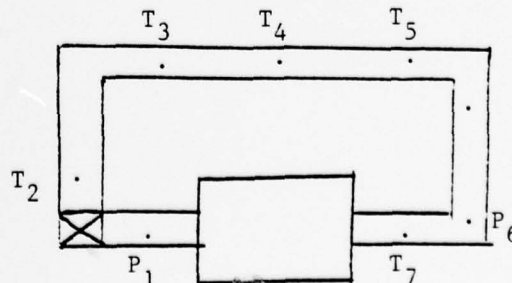


Voltages

P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>4</sub> Ch. 4 0.05V/div  
Time Scale 5msec/div  
Sustainer Voltage 25.8kV  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

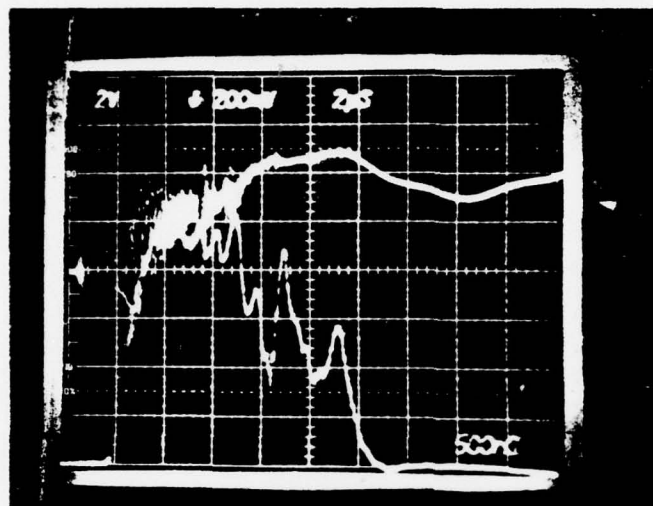
Analyzed Data:

$$E = 54.08$$



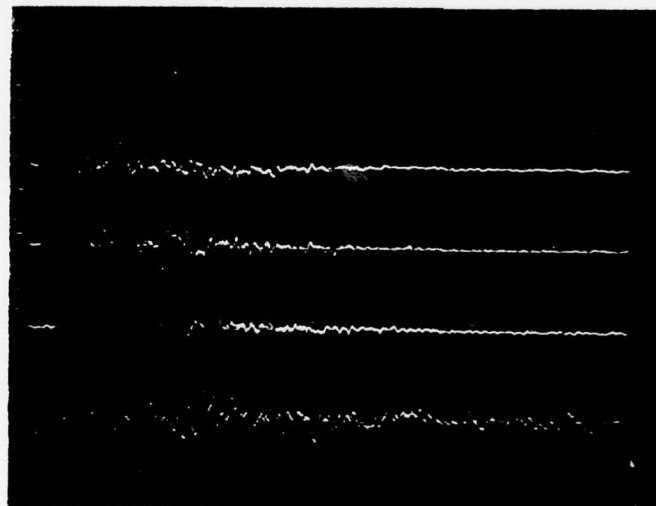
# PVC Circulator Experimental Data

Page 159  
No. 5433  
Date 11 July 1978



## Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2msec/div  
Inverted? Yes No
2. Lower Trace  
Voltage 2V /div  
Time Scale 500nsec/div  
Inverted? Yes No  
Attenuation \_\_\_\_\_



## Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>4</sub> Ch. 4 0.05V/div

Time Scale 20msec/div

Sustainer Voltage 25.8kV

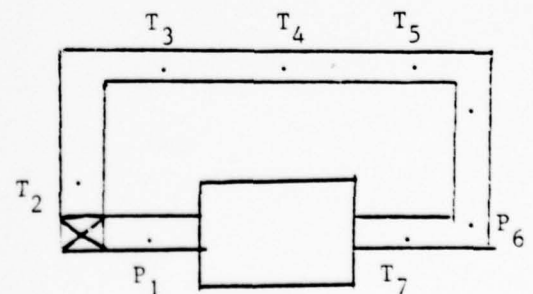
Flow? On Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

E = 59.15

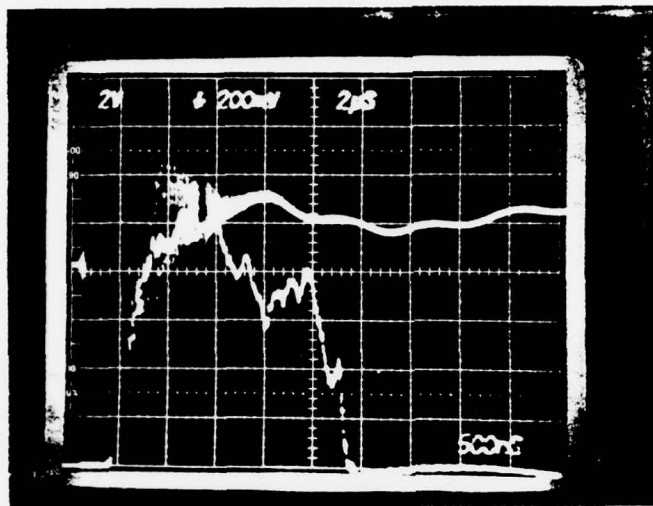


# PVC Circulator Experimental Data

Page 160

No. 5435

Date 11 July 1978



## Gun Data

1. Upper Trace

Voltage 200mV/div

Time Scale 2μsec/div

Inverted? (Yes) No

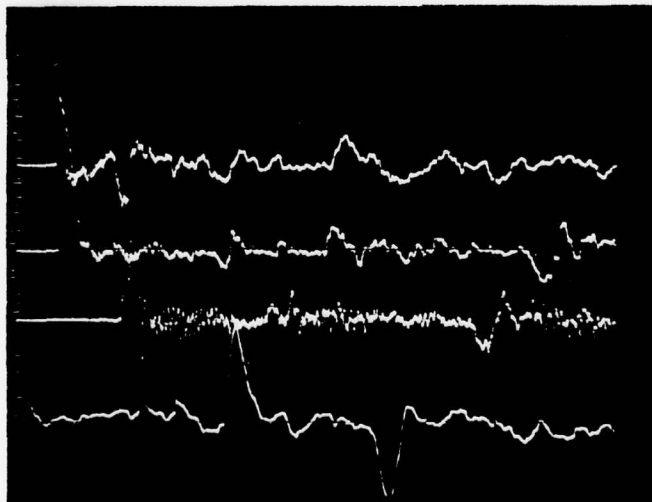
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



## Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5.5</sub> Ch. 3 0.02V/div

T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

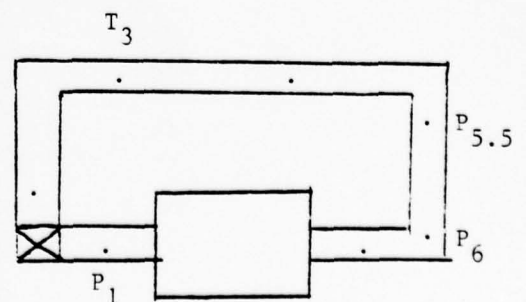
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: No muffler

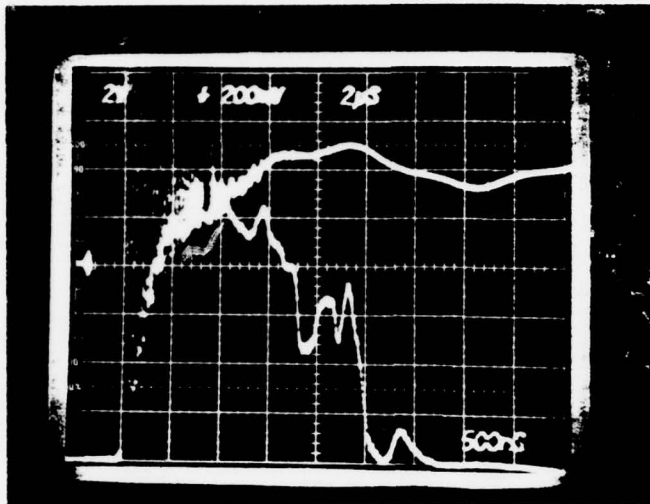
Analyzed Data:

$$E = 59.15$$



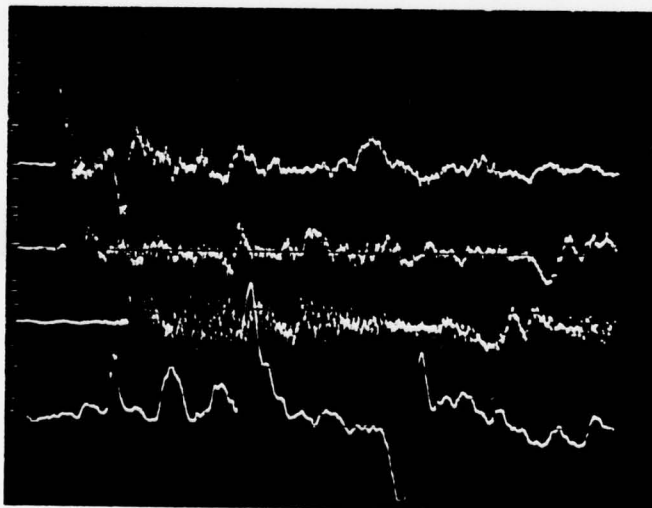
PVC Circulator Experimental Data

Page 161  
 No. 5436  
 Date 11 July 1978



Gun Data

1. Upper Trace  
 Voltage 200mV/div  
 Time Scale 2μsec/div  
 Inverted? (Yes) No
2. Lower Trace  
 Voltage 2V/div  
 Time Scale 500nsec/div  
 Inverted? Yes (No)  
 Attenuation \_\_\_\_\_

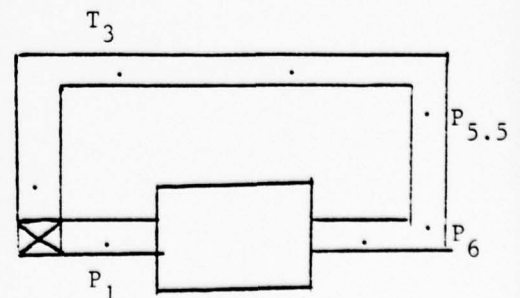


Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
 P<sub>6</sub> Ch. 2 0.02V/div  
 P<sub>5.5</sub> Ch. 3 0.02V/div  
 T<sub>3</sub> Ch. 4 0.05V/div  
 Time Scale 5msec/div  
 Sustainer Voltage 25.8kV  
 Flow? (On) Off  
 Gas Type N<sub>2</sub>  
 Notes: No muffler

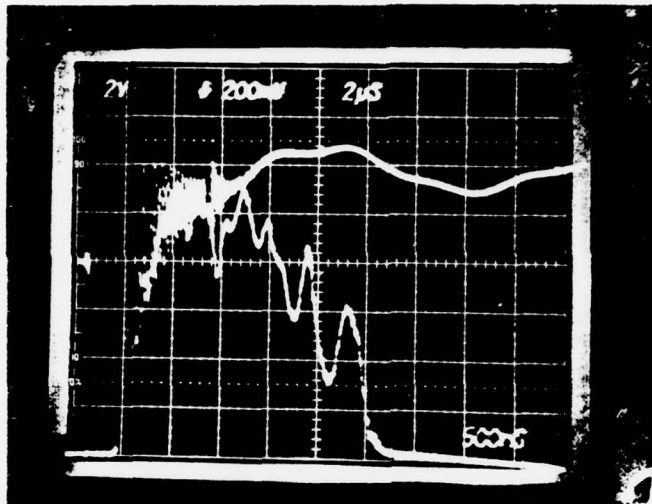
Analyzed Data:

$$E = 65.91$$



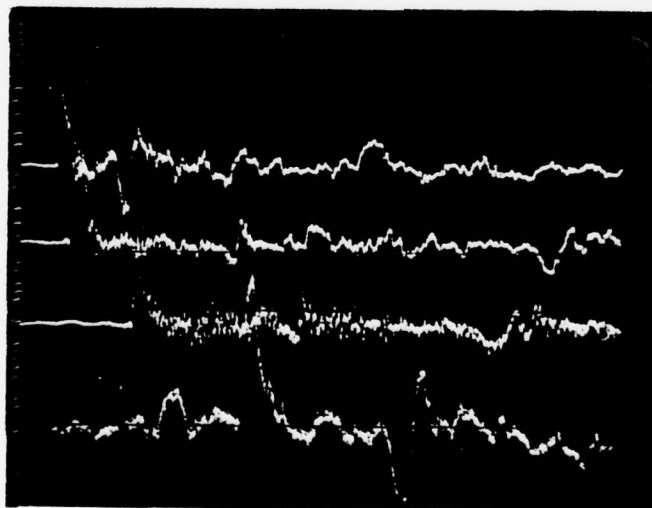
PVC Circulator Experimental Data

Page 162  
No. 5437  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



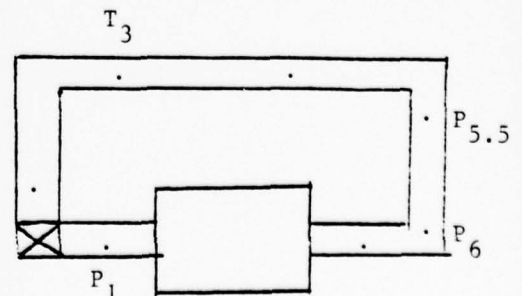
Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5.5</sub> Ch. 3 0.02V/div  
T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 5msec/div  
Sustainer Voltage 25.8kV  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: amp. not in circuit,  
no muffler

Analyzed Data:

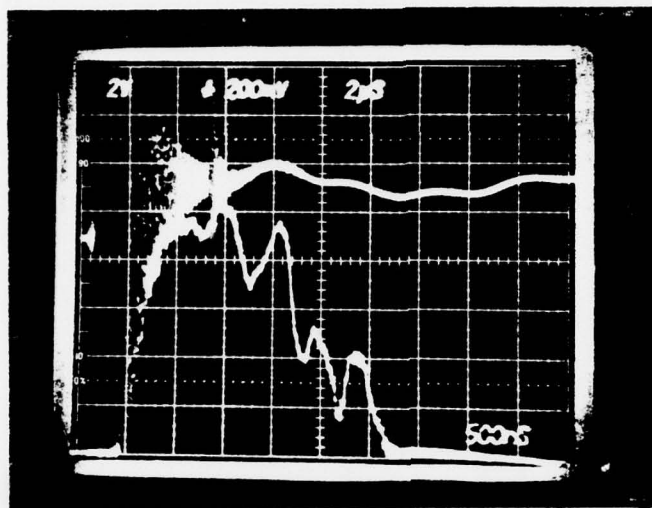
$$E = 65.91$$





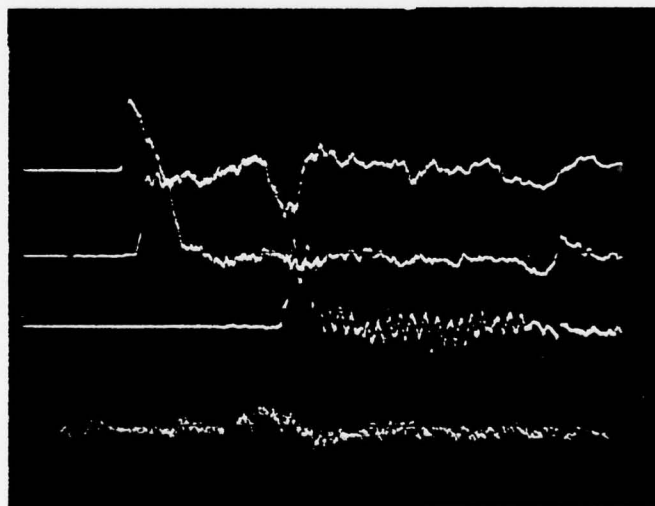
PVC Circulator Experimental Data

Page 163  
No. 5438  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



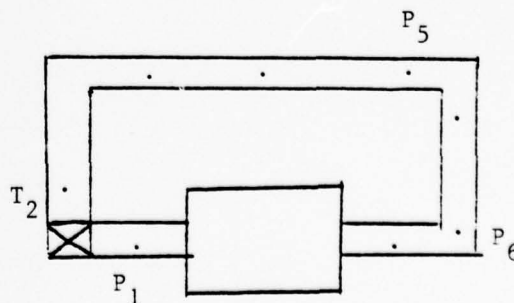
Voltages

- $P_1$  Ch. 1 0.02V/div  
 $P_6$  Ch. 2 0.02V/div  
 $P_5$  Ch. 3 0.02V/div  
 $T_2$  Ch. 4 0.05V/div  
Time Scale 2msec/div  
Sustainer Voltage 25.8kV\*  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: no muffler

Analyzed Data:

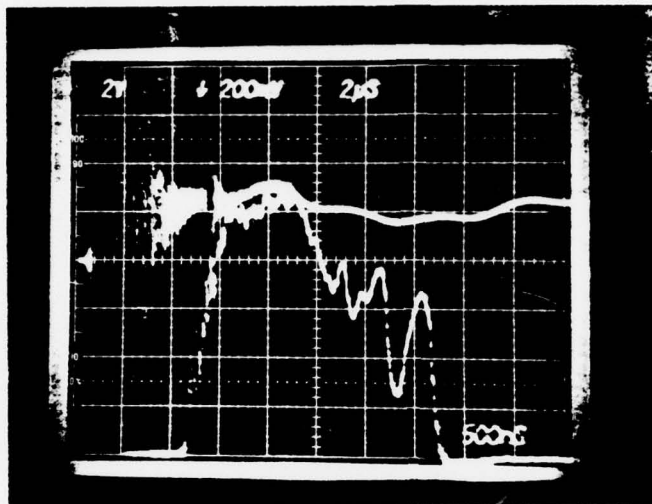
$$E = 60.84^*$$

\* Assumed value



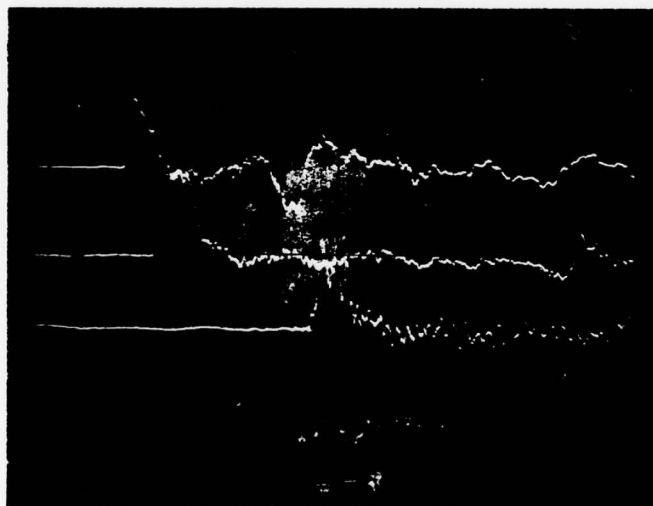
PVC Circulator Experimental Data

Page 164  
No. 5439  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500msec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



Voltages

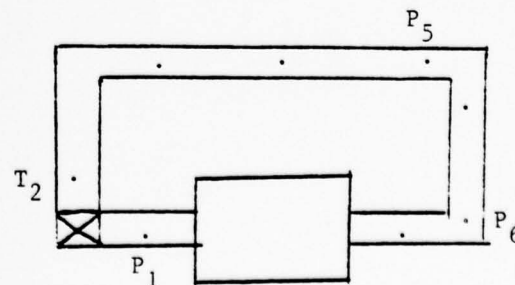
- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>2</sub> Ch. 4 0.05V/div

Time Scale 2msec/div  
Sustainer Voltage 25.8kV\*  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: no muffler

Analyzed Data:

$$E = 64.22^*$$

\*Assumed value

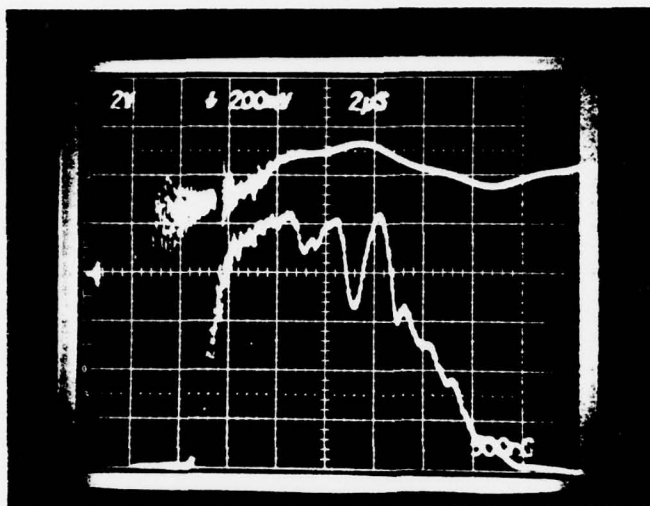


PVC Circulator Experimental Data

Page 165

No. 5441

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 200mV/div

Time Scale 2μsec/div

Inverted? (Yes) No

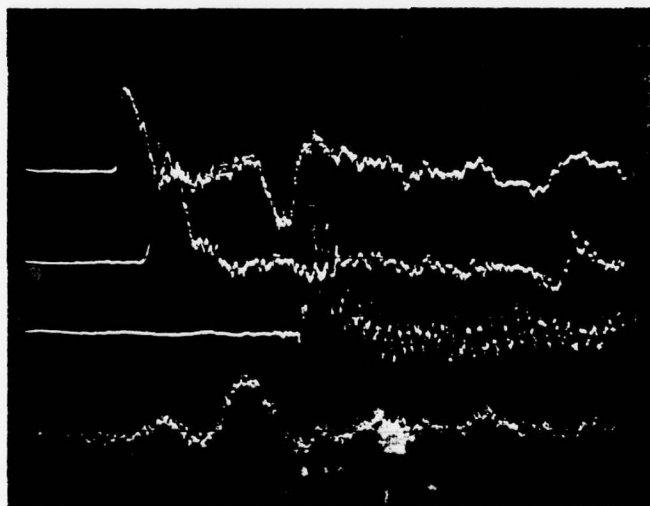
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>2</sub> Ch. 4 0.02V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV\*

Flow? (On) Off

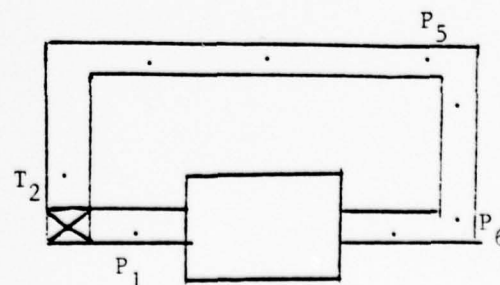
Gas Type N<sub>2</sub>

Notes: no muffler

Analyzed Data:

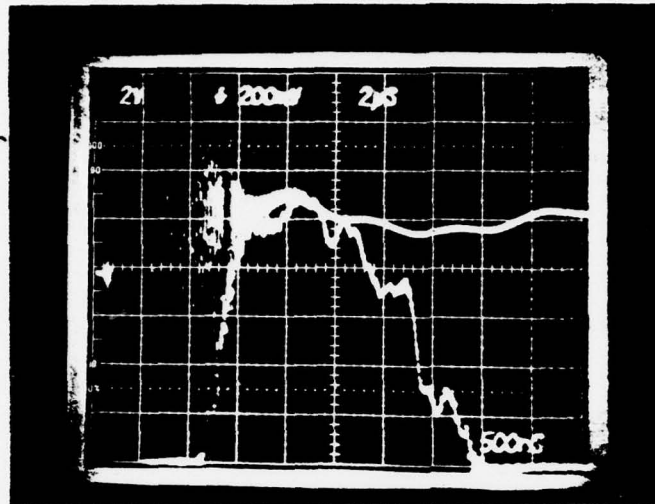
$$E = 72.67^*$$

\*Assumed value



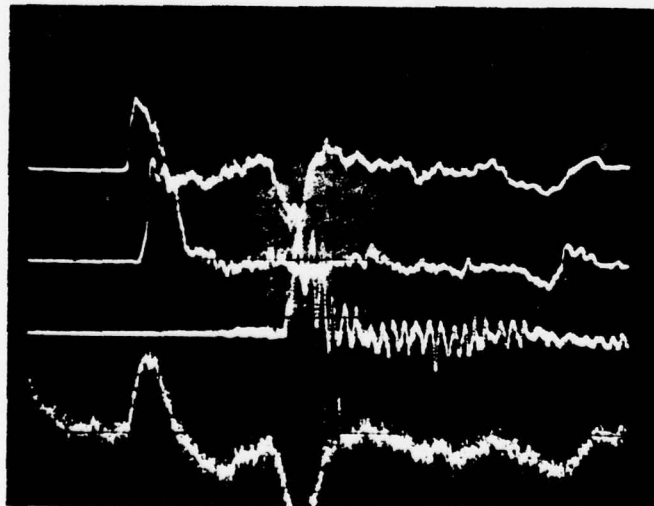
PVC Circulator Experimental Data

Page 166  
No. 5443  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



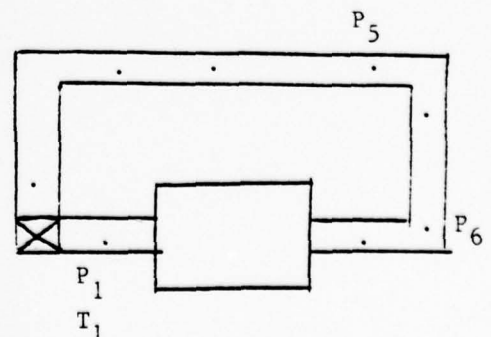
Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>1</sub> Ch. 4 0.05V/div  
Time Scale 2msec/div  
Sustainer Voltage 25.8kV\*  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: no muffler

Analyzed Data:

$$E = 67.60^*$$

\*Assumed value

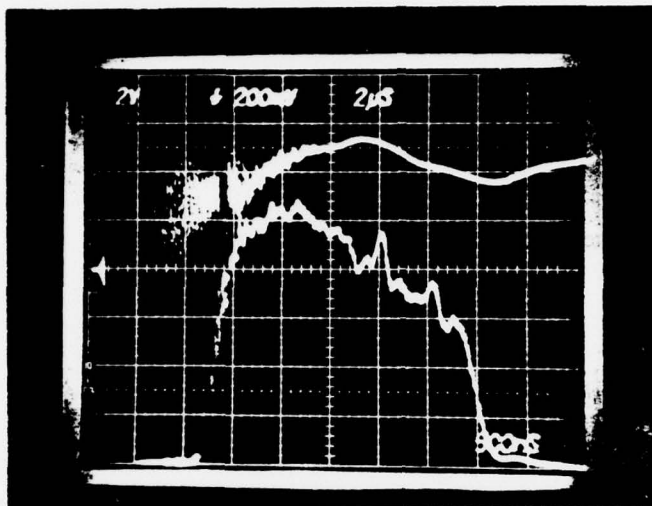


PVC Circulator Experimental Data

Page 167

No. 5444

Date 11 July 1978



Gun Data

1. Upper Trace

Voltage 200mV/div

Time Scale 2µsec/div

Inverted? (Yes) No

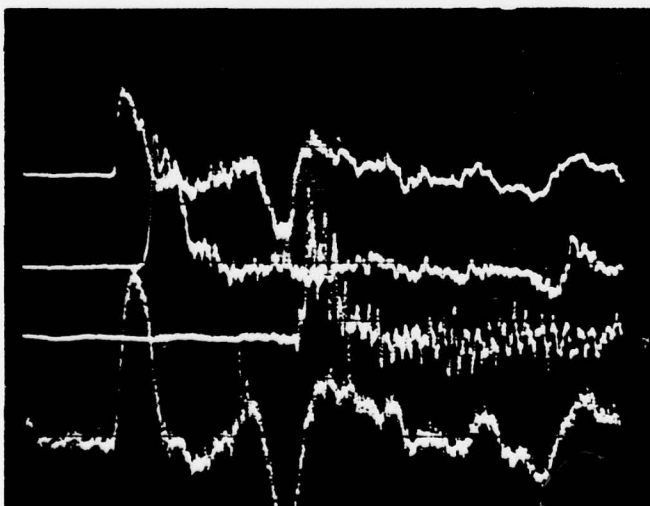
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>1</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV\*

Flow? On Off

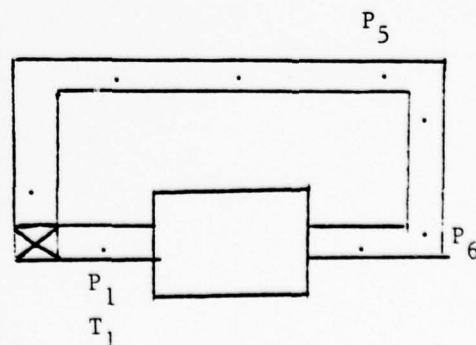
Gas Type N<sub>2</sub>

Notes: no muffler

Analyzed Data:

$$E = 77.74^*$$

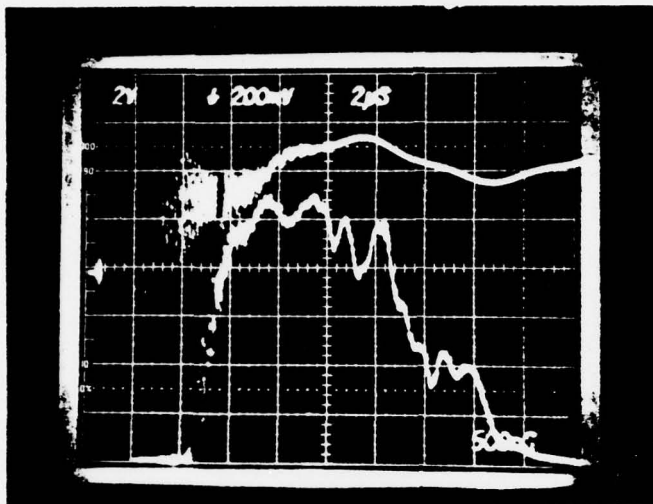
\*Assumed value





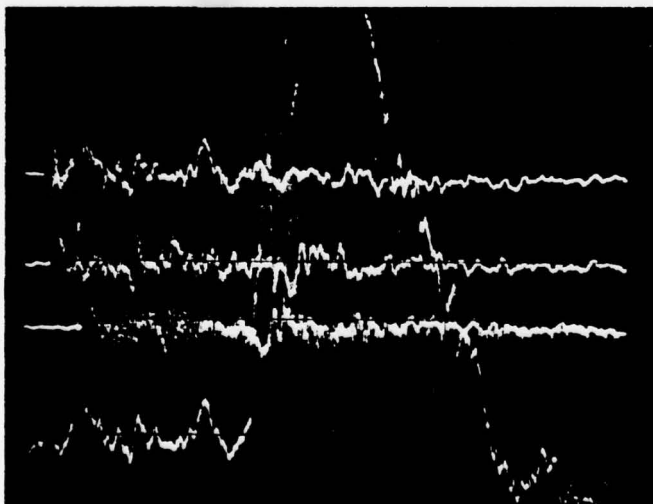
PVC Circulator Experimental Data

Page 168  
No. 5445  
Date 11 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



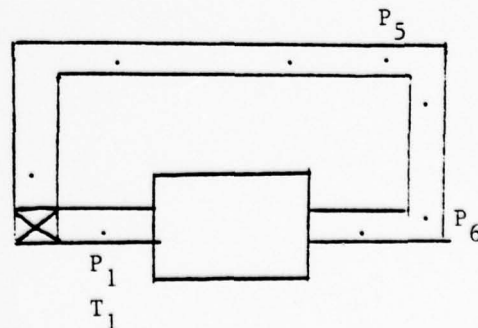
Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>1</sub> Ch. 4 0.10V/div  
Time Scale 10msec/div  
Sustainer Voltage 25.8kV\*  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: no muffler

Analyzed Data:

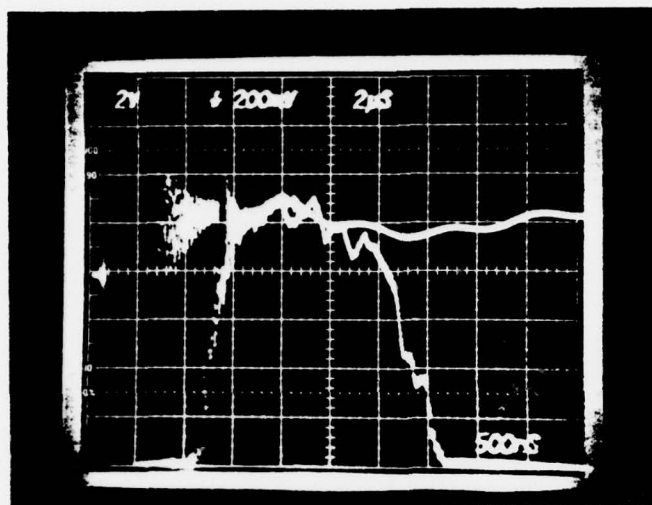
$$E = 77.74^*$$

\* Assumed value



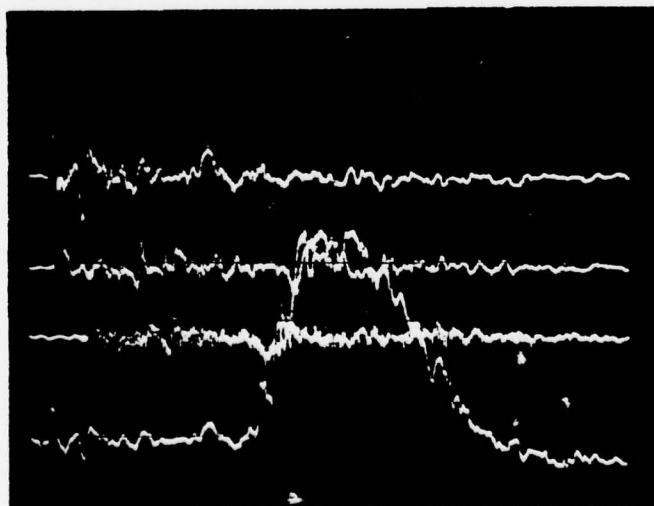
# PVC Circulator Experimental Data

Page 169  
No. 5446  
Date 11 July 1978



## Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



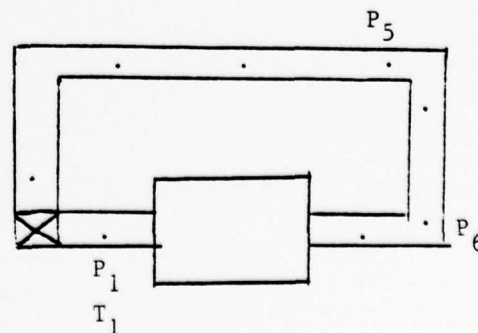
## Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>1</sub> Ch. 4 0.20V/div  
Time Scale 10msec/div  
Sustainer Voltage 25.8kV\*  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: no muffler

## Analyzed Data:

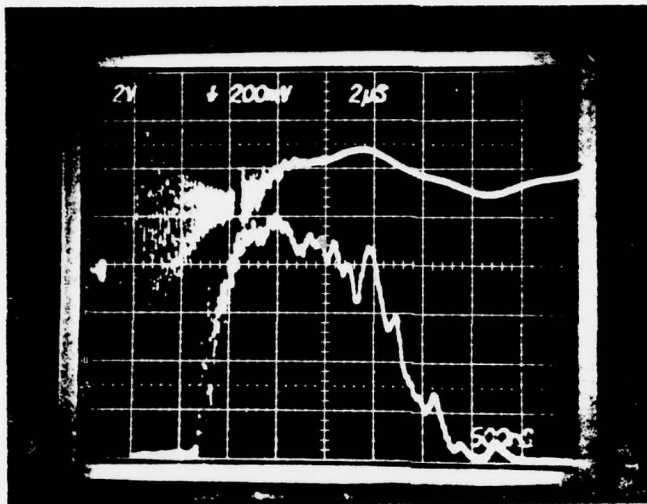
$$E = 67.60^*$$

\* Assumed value



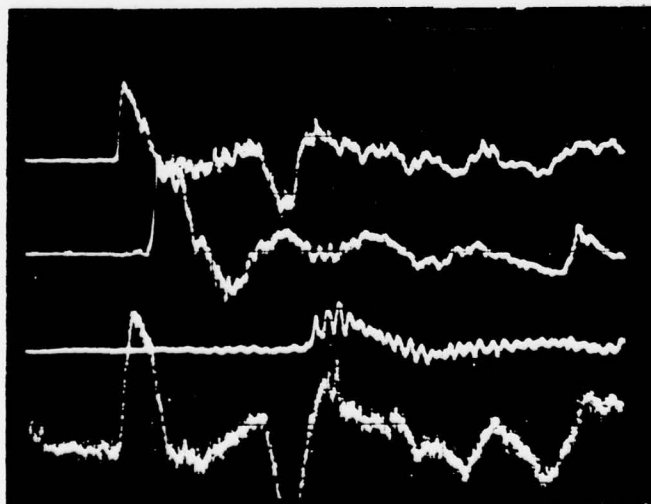
PVC Circulator Experimental Data

Page 170  
No. 5448  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



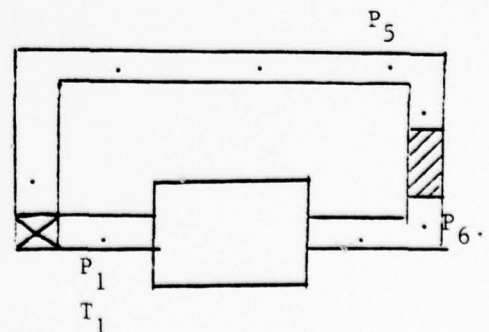
Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>5</sub> Ch. 2 0.02V/div  
P<sub>6</sub> Ch. 3 0.02V/div  
T<sub>1</sub> Ch. 4 0.05V/div

Time Scale 2msec/div  
Sustainer Voltage 25.8kV  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

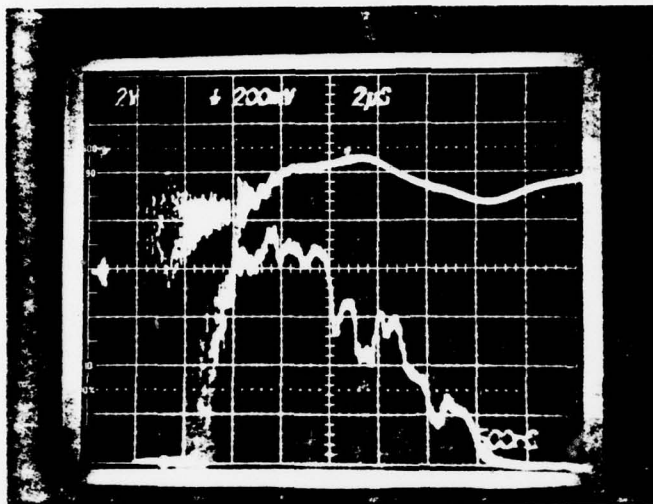
Analyzed Data:

$$E = 60.84$$



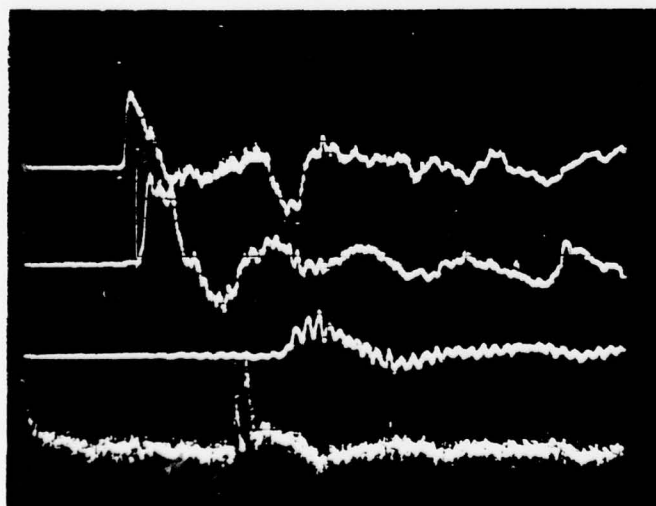
# PVC Circulator Experimental Data

Page 171  
No. 5449  
Date 12 July 1978



## Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_

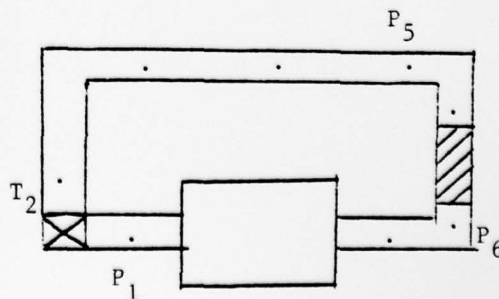


## Voltages

- $P_1$  Ch. 1 0.02V/div  
 $P_6$  Ch. 2 0.02V/div  
 $P_5$  Ch. 3 0.02V/div  
 $T_2$  Ch. 4 0.05V/div  
Time Scale 2msec/div  
Sustainer Voltage 25.8kV  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

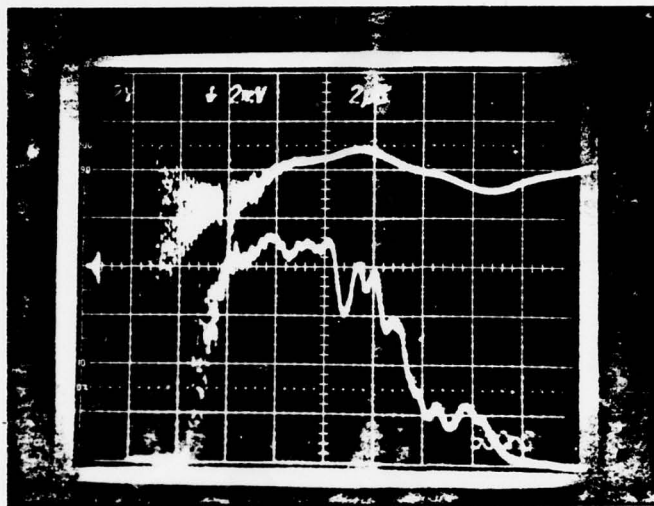
Analyzed Data:

$$E = 55.77$$



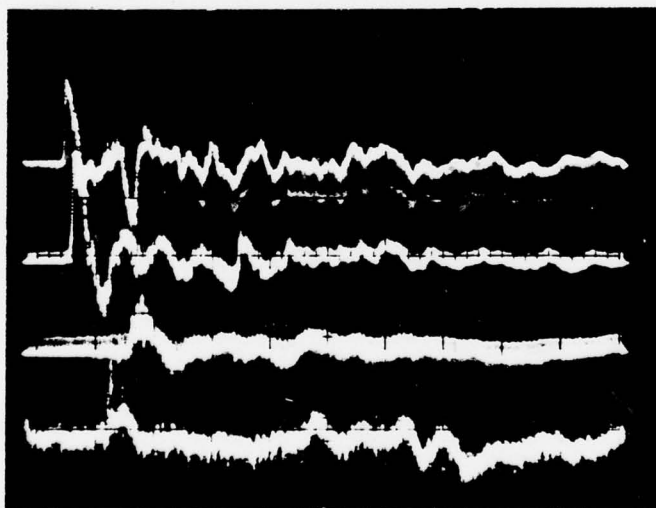
PVC Circulator Experimental Data

Page 172  
No. 5450  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 2mV /div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V /div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



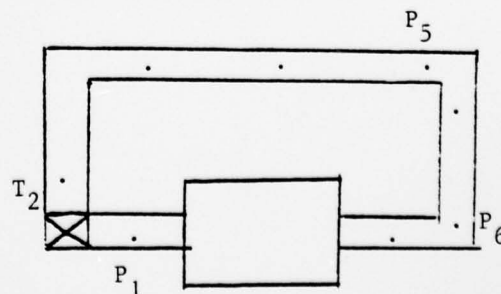
Voltages

- P<sub>1</sub> Ch. 1 0.02V /div  
P<sub>5</sub> Ch. 2 0.02V /div  
P<sub>6</sub> Ch. 3 0.02V /div  
T<sub>2</sub> Ch. 4 0.05V /div

Time Scale 5msec /div  
Sustainer Voltage 25.8kV  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

Analyzed Data:

$$E = 64.22$$



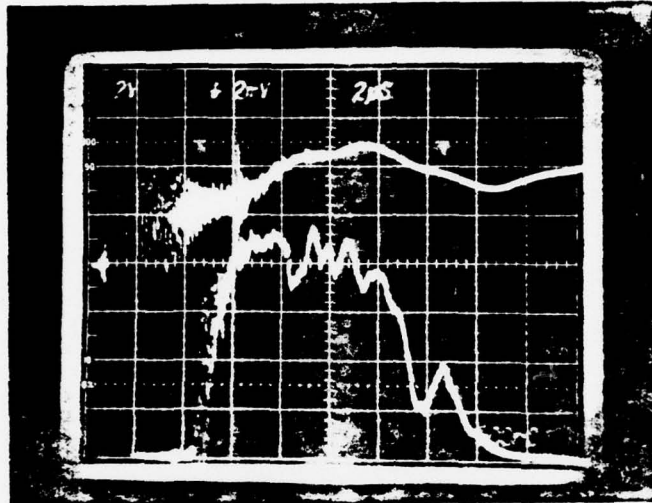


PVC Circulator Experimental Data

Page 173

No. 5451

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 2mV /div

Time Scale 2μsec/div

Inverted? (Yes) No

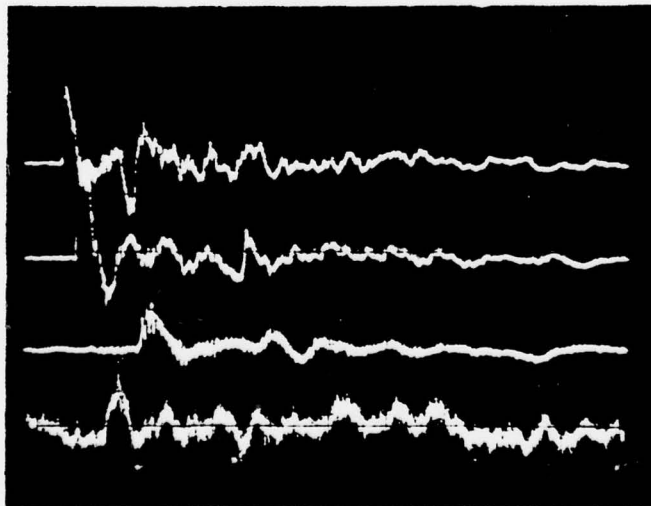
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V /div

P<sub>5</sub> Ch. 2 0.02V /div

P<sub>6</sub> Ch. 3 0.02V /div

T<sub>2</sub> Ch. 4 0.05V /div

Time Scale 5msec /div

Sustainer Voltage 25.8kV

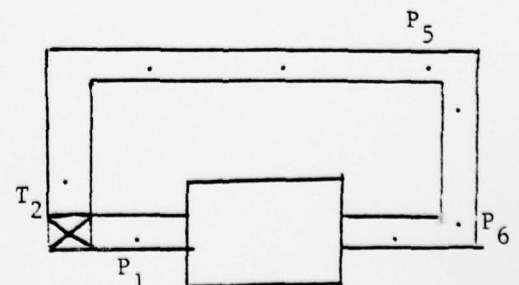
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

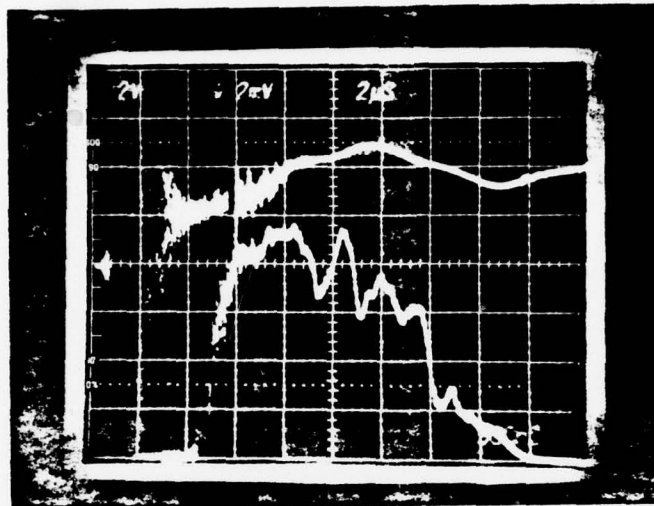
Analyzed Data:

$$E = 59.15$$



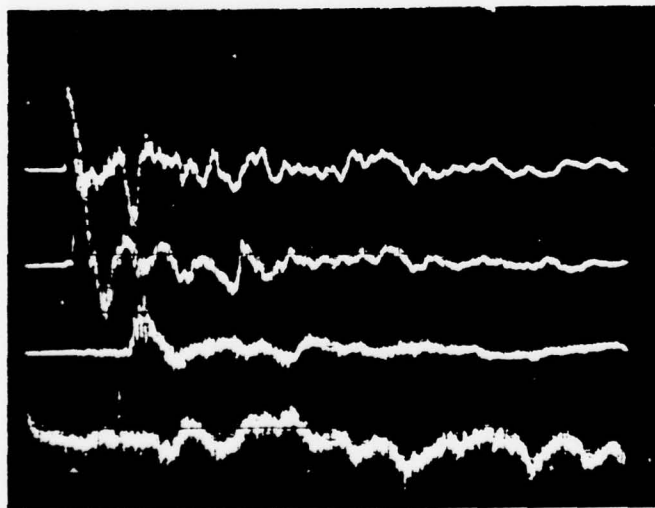
PVC Circulator Experimental Data

Page 174  
No. 5452  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 2mV/div  
Time Scale 2µsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



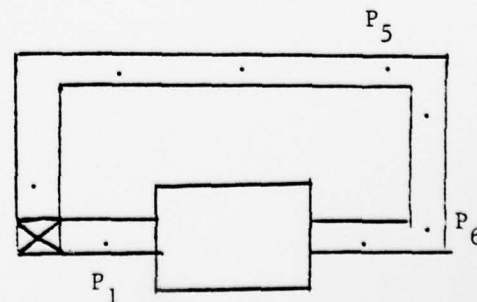
Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>5</sub> Ch. 2 0.02V/div  
P<sub>6</sub> Ch. 3 0.02V/div  
T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 5msec/div  
Sustainer Voltage 25.8kV  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

Analyzed Data:

$$E = 64.22$$

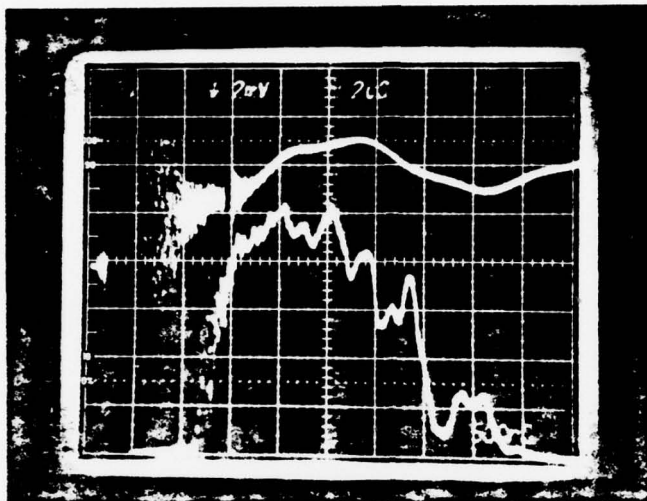


PVC Circulator Experimental Data

Page 175

No. 5453

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 2mV/div

Time Scale 2μsec/div

Inverted? (Yes) No

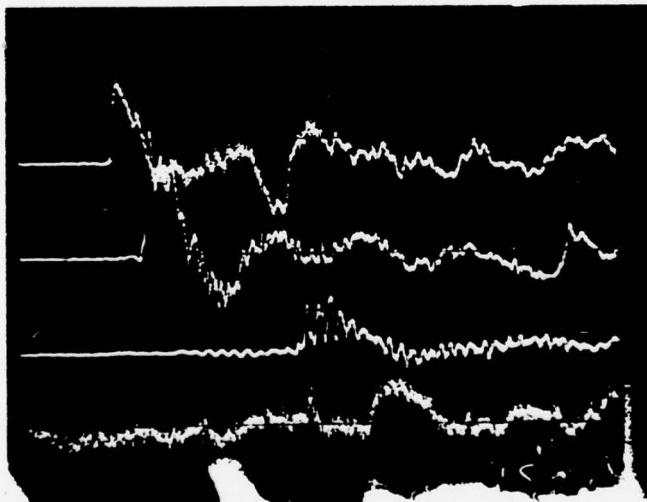
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>5</sub> Ch. 2 0.02V/div

P<sub>6</sub> Ch. 3 0.02V/div

T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

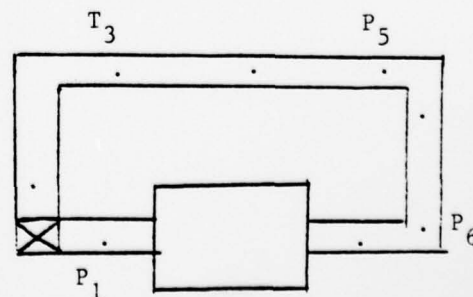
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

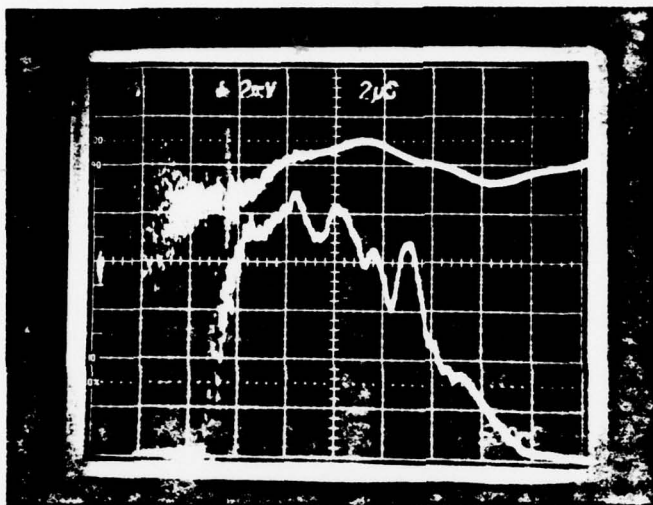
Analyzed Data:

$$E = 67.6$$



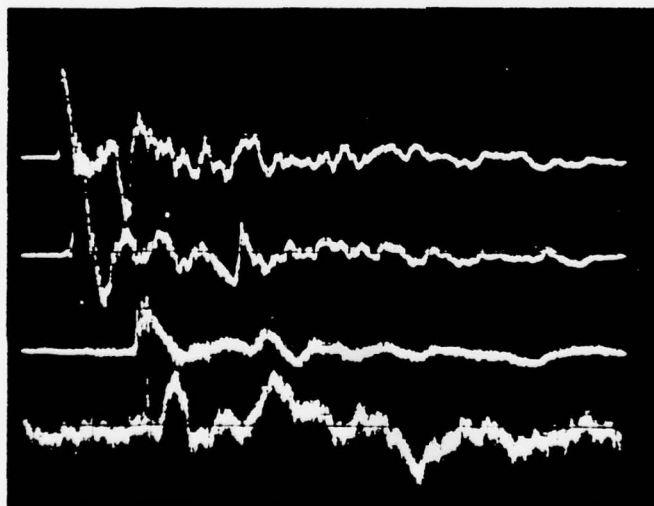
PVC Circulator Experimental Data

Page 176  
No. 5454  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 2mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_

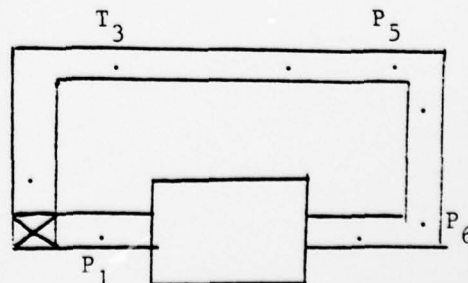


Voltages

P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>5</sub> Ch. 2 0.02V/div  
P<sub>6</sub> Ch. 3 0.02V/div  
T<sub>3</sub> Ch. 4 0.05V/div  
Time Scale 5msec/div  
Sustainer Voltage 26.0kV  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

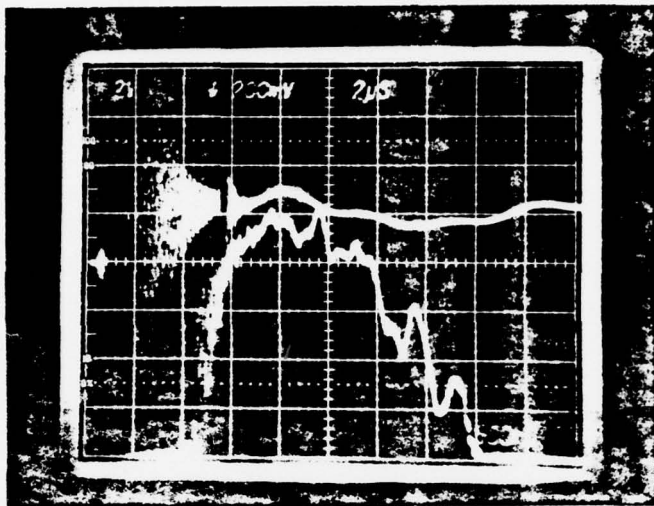
Analyzed Data:

$$E = 74.93643$$



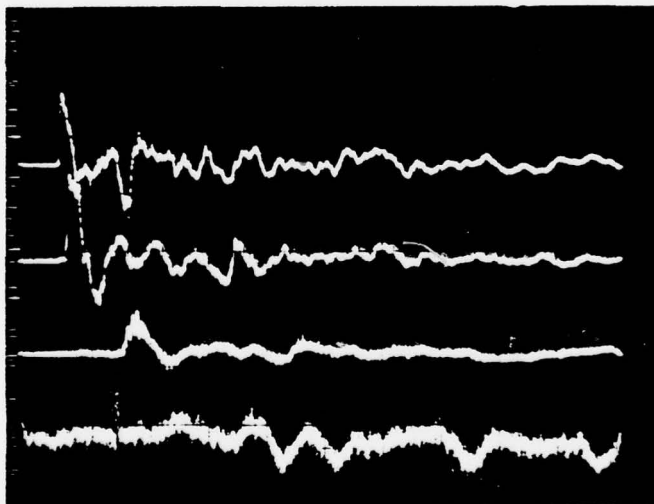
PVC Circulator Experimental Data

Page 177  
No. 5456  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_

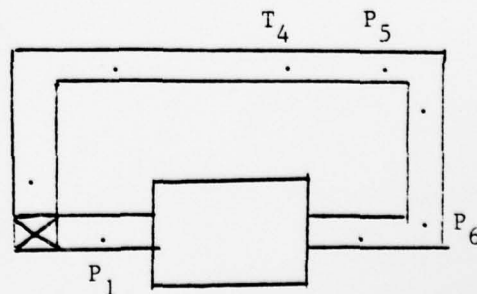


Voltages

P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>5</sub> Ch. 2 0.02V/div  
P<sub>6</sub> Ch. 3 0.02V/div  
T<sub>4</sub> Ch. 4 0.02V/div  
Time Scale 5msec/div  
Sustainer Voltage 25.8kV  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

Analyzed Data:

$$E = 67.6$$



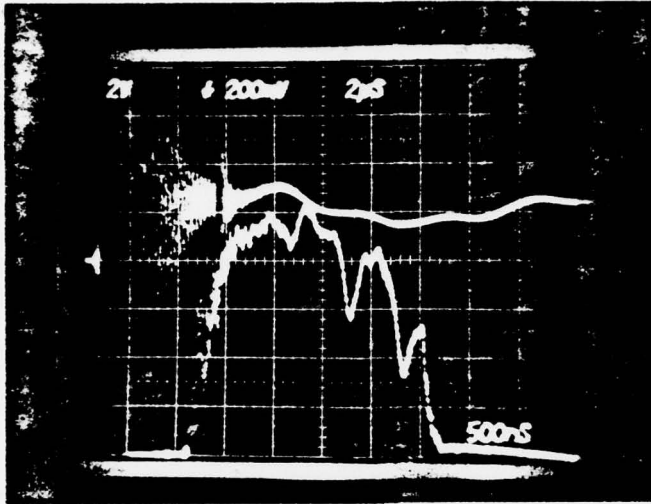


### PVC Circulator Experimental Data

Page 178

No. 5457

Date 12 July 1978



## Gun Data

- ## 1. Upper Trace

Voltage 200mV/div

Time Scale 2μsec/div

Inverted? (Yes) No

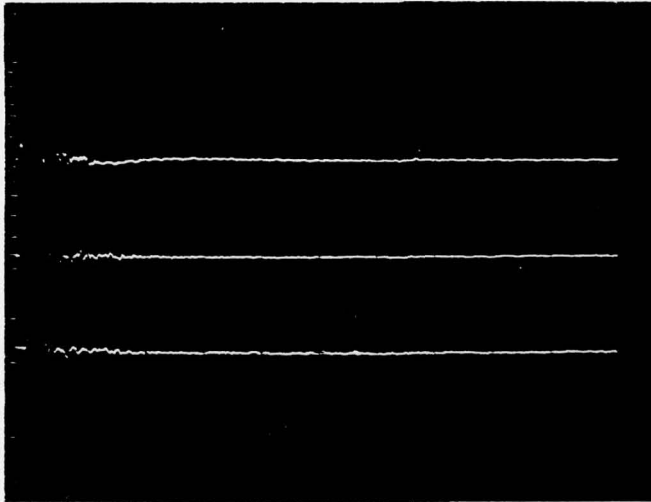
- ## 2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



## Voltages

P<sub>1</sub> Ch. 1 0.02V/div

P<sub>5</sub> Ch. 2 0.02V/div

P<sub>6</sub> Ch. 3 0.02V/div

T<sub>4</sub> Ch. 4 0.05V/div

Time Scale 50msec /div

Sustainer Voltage 25.8kV

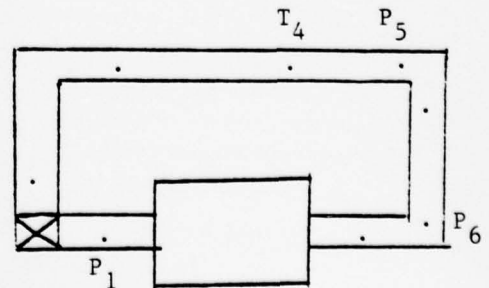
Flow? ☒ On ☐ Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

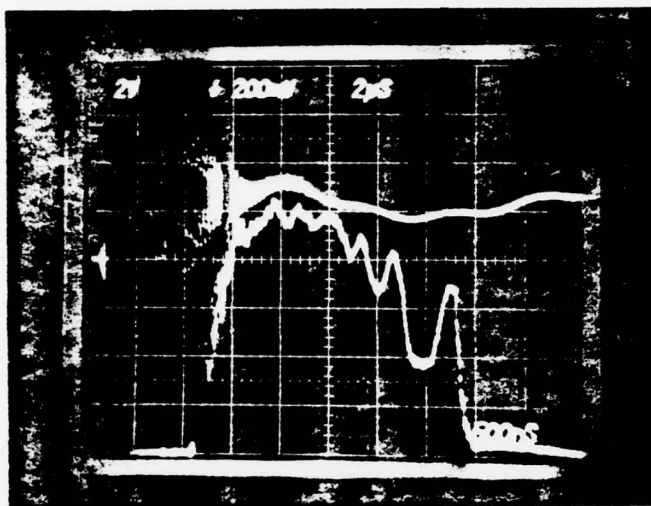
Analyzed Data:

$$E = 64.22$$



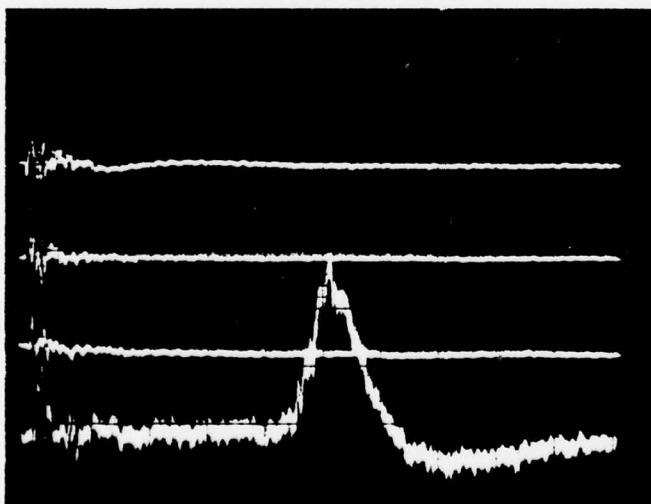
# PVC Circulator Experimental Data

Page 179  
No. 5459  
Date 12 July 1978



## Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? Yes No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes No  
Attenuation \_\_\_\_\_



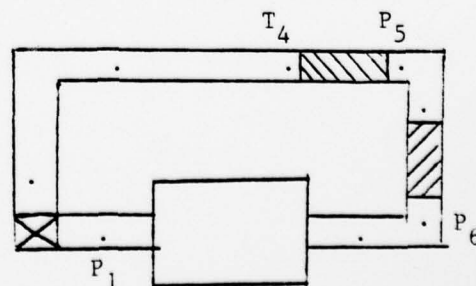
## Voltages

- P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>5</sub> Ch. 2 0.02V/div  
P<sub>6</sub> Ch. 3 0.02V/div  
T<sub>4</sub> Ch. 4 0.05V/div

Time Scale 50msec/div  
Sustainer Voltage 25.8kV  
Flow? On Off  
Gas Type N<sub>2</sub>  
Notes: both mufflers in

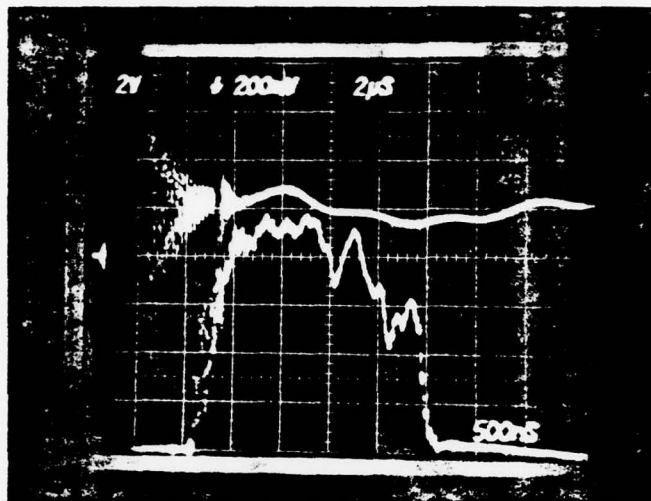
Analyzed Data:

$$E = 72.67$$



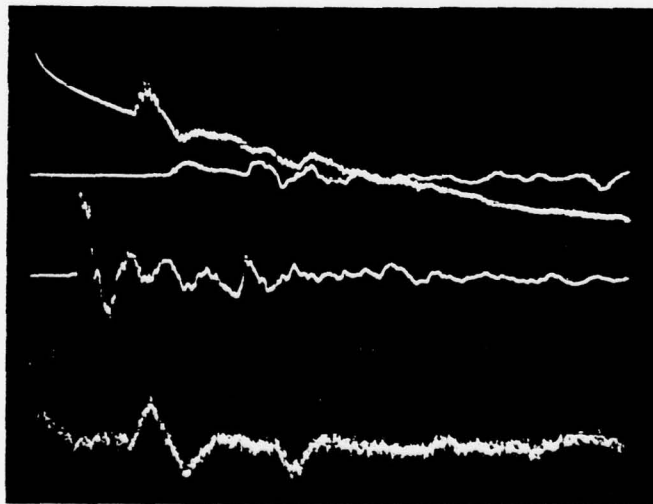
PVC Circulator Experimental Data

Page 180  
No. 5460  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>5</sub> Ch. 4 0.05V/div

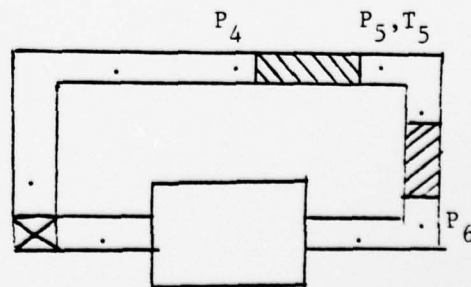
Time Scale 5msec/div  
Sustainer Voltage 25.8kV\*  
Flow? On (Off)  
Gas Type N<sub>2</sub>

Notes: both mufflers in  
Channel 3 was hit by pulse  
at triggering time

Analyzed Data:

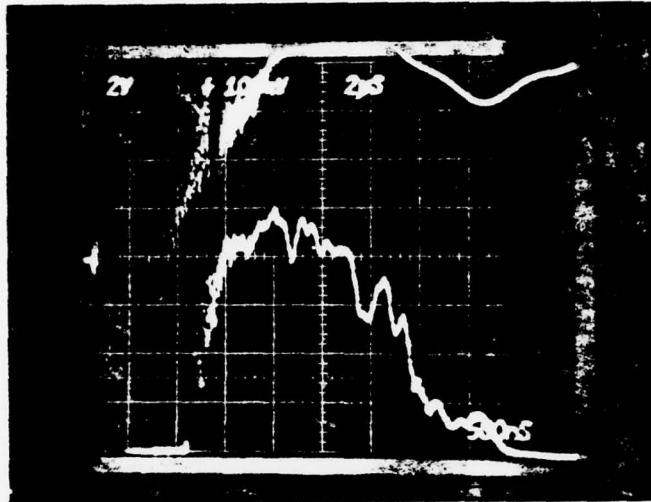
$$E = 60.84^*$$

\* Assumed value



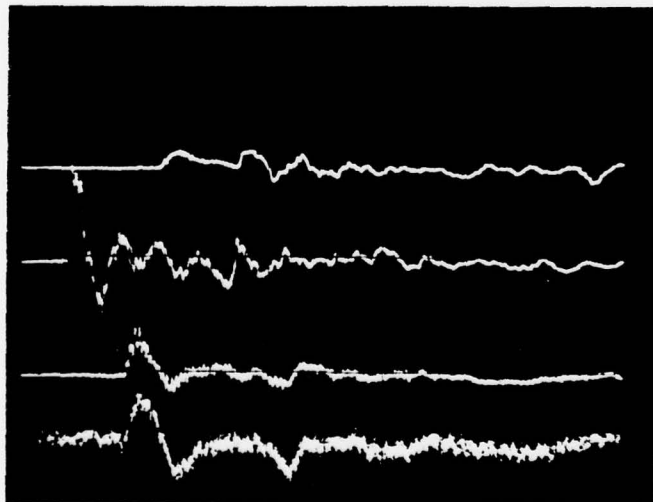
PVC Circulator Experimental Data

Page 181  
No. 5461  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV\*

Flow? On (Off)

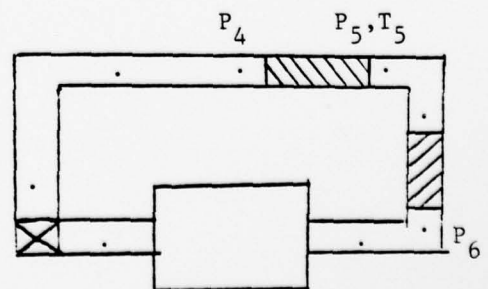
Gas Type N<sub>2</sub>

Notes: same as 5460 with  
stable channel 3

Analyzed Data:

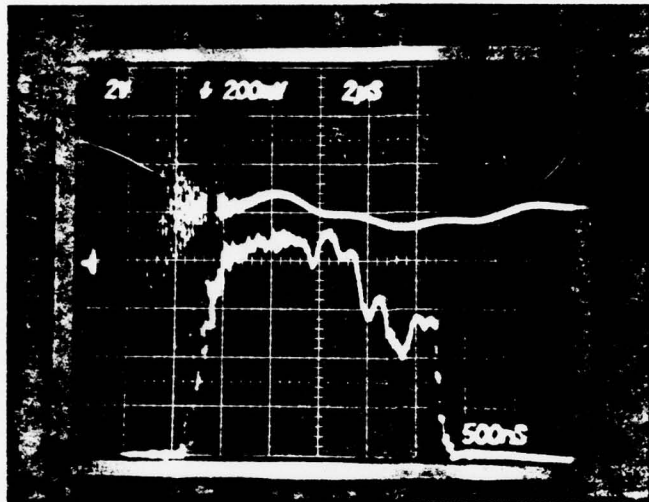
$$E = 62.53^*$$

\* Assumed value



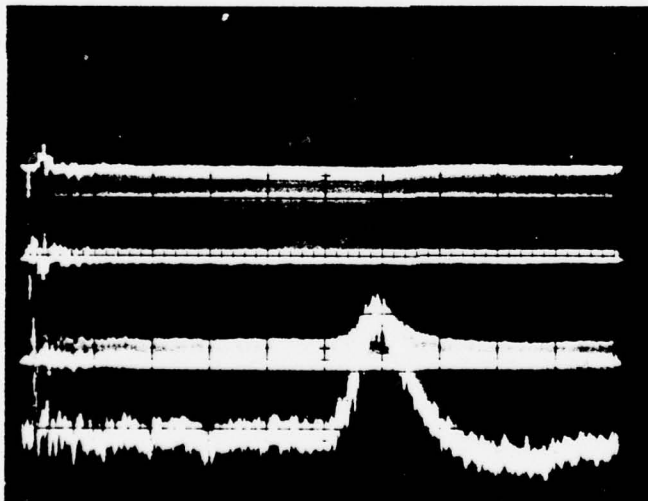
PVC Circulator Experimental Data

Page 182  
No. 5462  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 200mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



Voltages

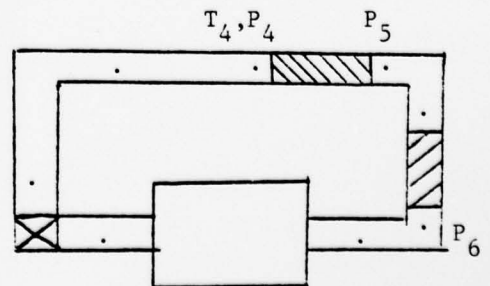
- P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>4</sub> Ch. 4 0.05V/div

Time Scale 50msec/div  
Sustainer Voltage 25.8kV\*  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

Analyzed Data:

$$E = 64.22^*$$

\* Assumed value



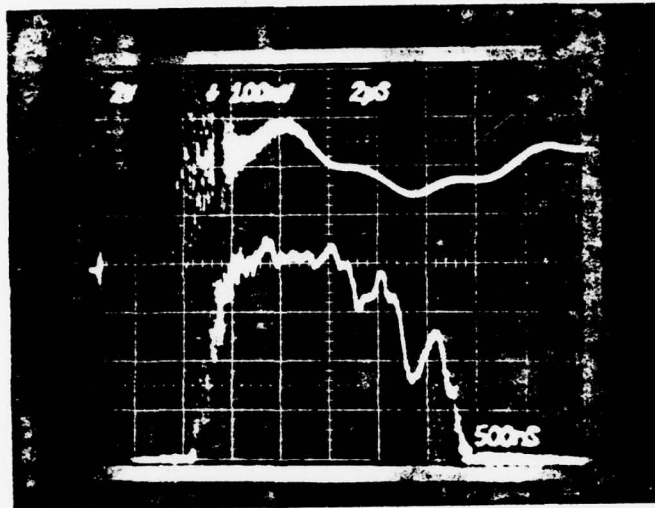


PVC Circulator Experimental Data

Page 183

No. 5463

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 2μsec/div

Inverted? (Yes) No

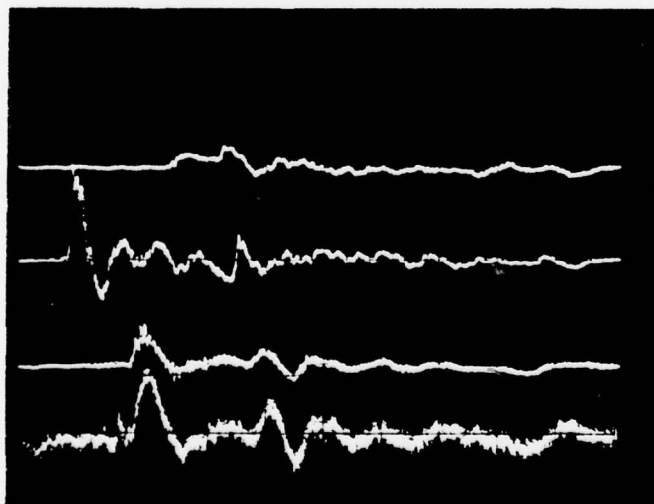
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

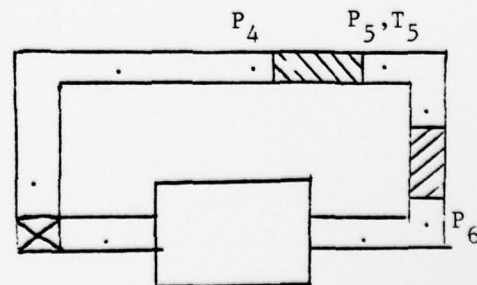
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 57.46$$

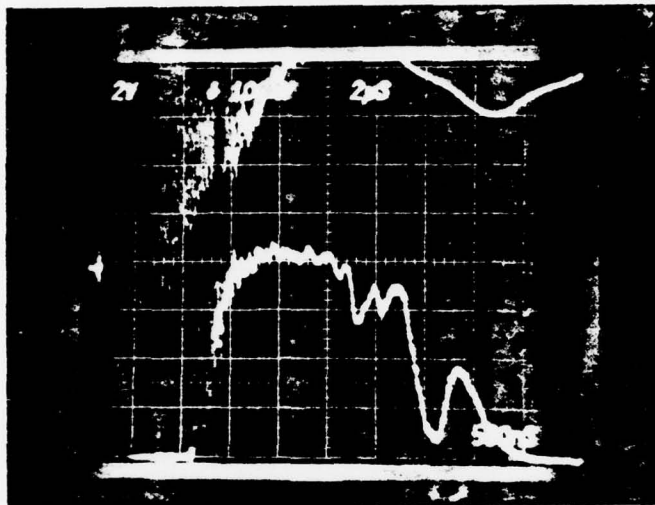


PVC Circulator Experimental Data

Page 184

No. 5464

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 2μsec/div

Inverted? (Yes) No

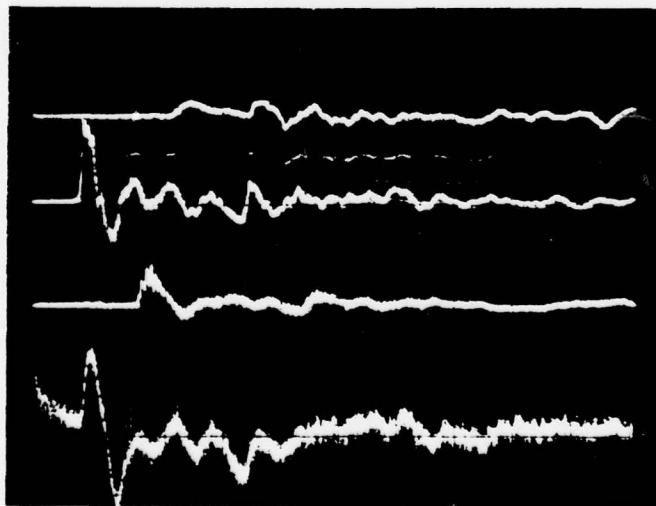
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>6</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

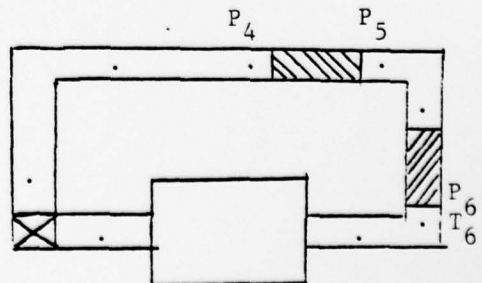
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

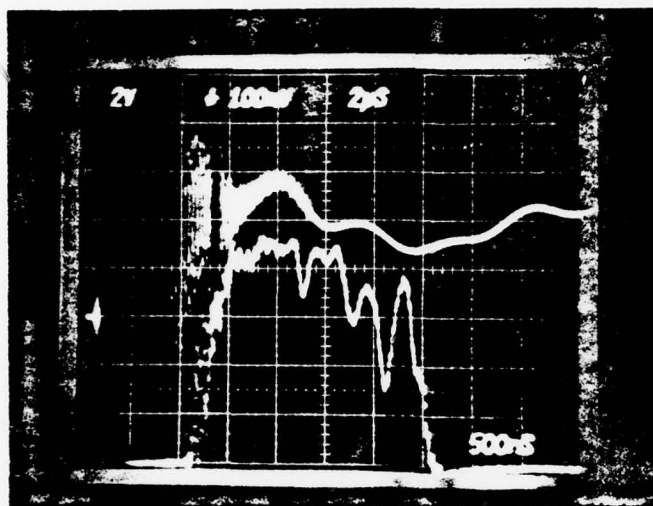
Analyzed Data:

$$E = 57.46$$



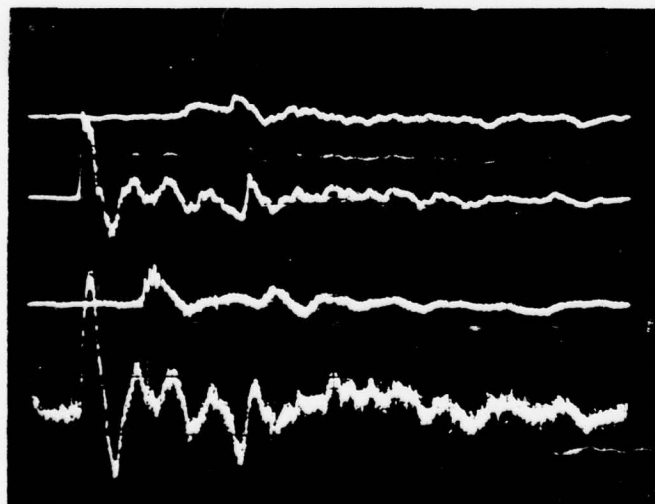
PVC Circulator Experimental Data

Page 185  
 No. 5466  
 Date 12 July 1978



Gun Data

1. Upper Trace  
 Voltage 100mV/div  
 Time Scale 2μsec/div  
 Inverted? (Yes) No
2. Lower Trace  
 Voltage 2V /div  
 Time Scale 500nsec/div  
 Inverted? Yes (No)  
 Attenuation \_\_\_\_\_



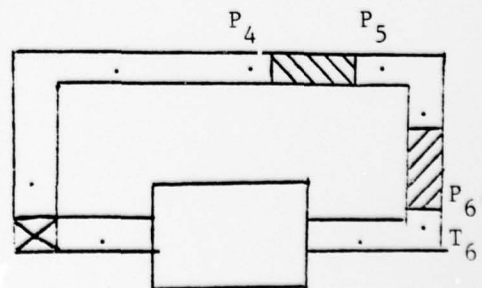
Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
 P<sub>6</sub> Ch. 2 0.02V/div  
 P<sub>5</sub> Ch. 3 0.02V/div  
 T<sub>6</sub> Ch. 4 0.05V/div

Time Scale 5msec/div  
 Sustainer Voltage 25.8kV  
 Flow? (On) Off  
 Gas Type N<sub>2</sub>  
 Notes: \_\_\_\_\_

Analyzed Data:

$$E = 57.46$$

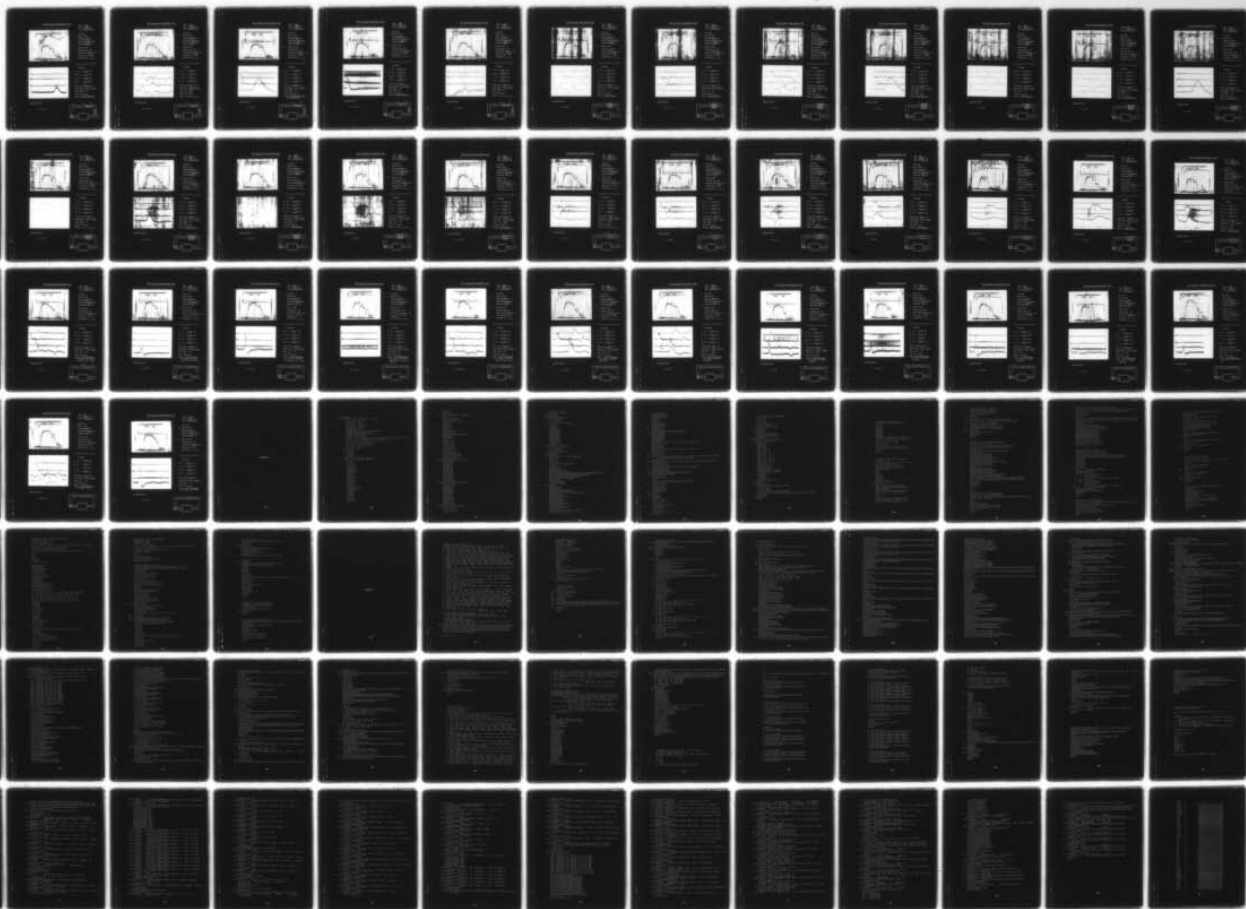


AD-A068 547

ALABAMA UNIV IN HUNTSVILLE SCHOOL OF SCIENCE AND ENG--ETC F/6 20/5  
INVESTIGATION OF TRANSIENT FLOW AND HEATING PROBLEMS CHARACTERI--ETC(U)  
MAR 79 C C SHIH, G R KARR, J F PERKINS DAAK40-77-C-0161  
UAH-RR-219 DRCPM-HEL-CR-79-8 NL

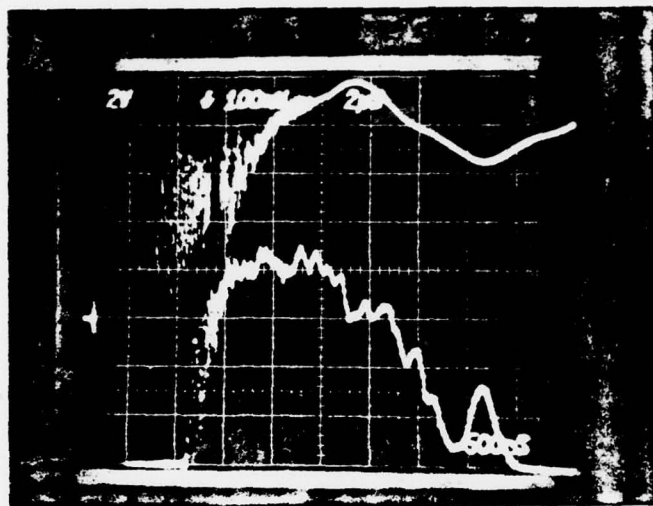
UNCLASSIFIED

3 OF 4  
AD  
A068547



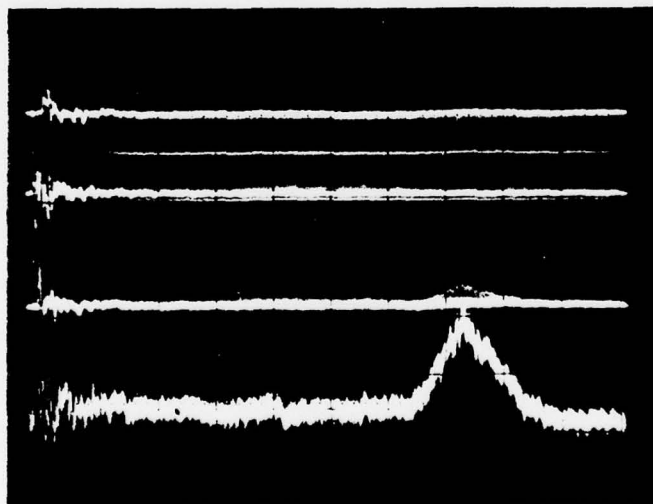
PVC Circulator Experimental Data

Page 186  
No. 5467  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 2μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_

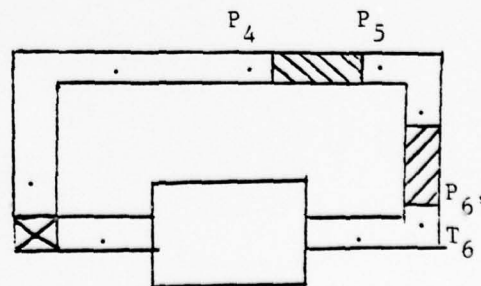


Voltages

P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>6</sub> Ch. 4 0.05V/div  
Time Scale 50msec/div  
Sustainer Voltage 25.8kV  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: heat pulse test

Analyzed Data:

$$E = 57.46$$



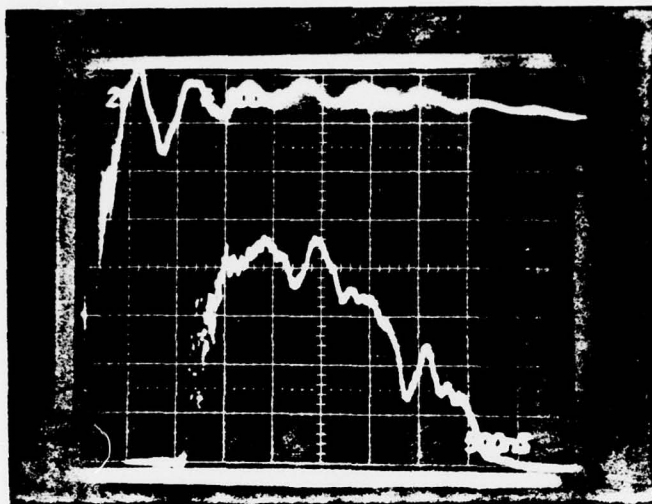


PVC Circulator Experimental Data

Page 187

No. 5468

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10μsec/div

Inverted? (Yes) No

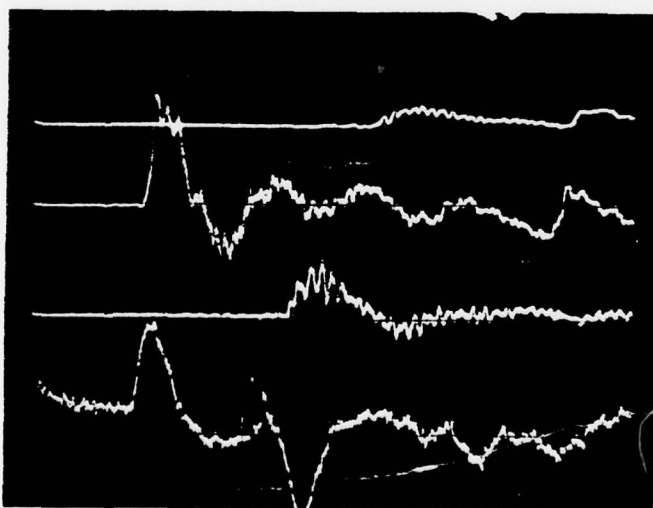
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>1</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

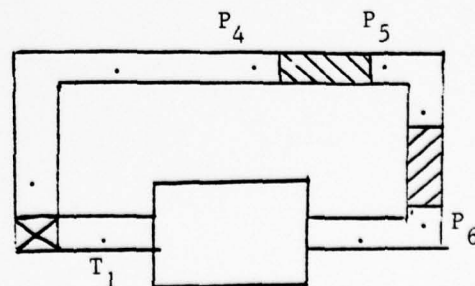
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes:           

Analyzed Data:

$$E = 60.84$$

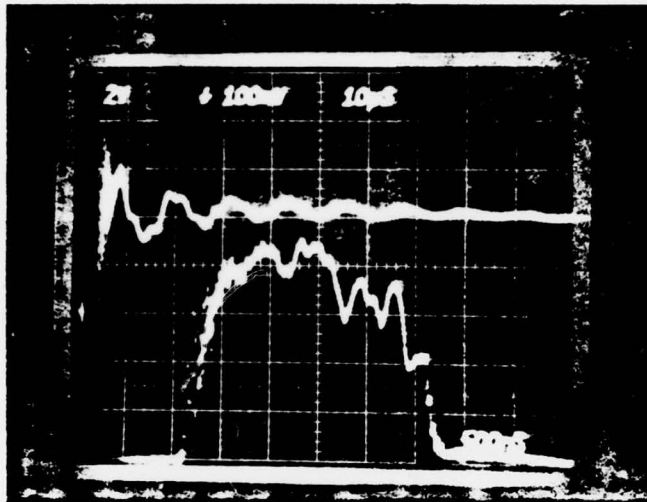


PVC Circulator Experimental Data

Page 188

No. 5469

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10ps/div

Inverted? (Yes) No

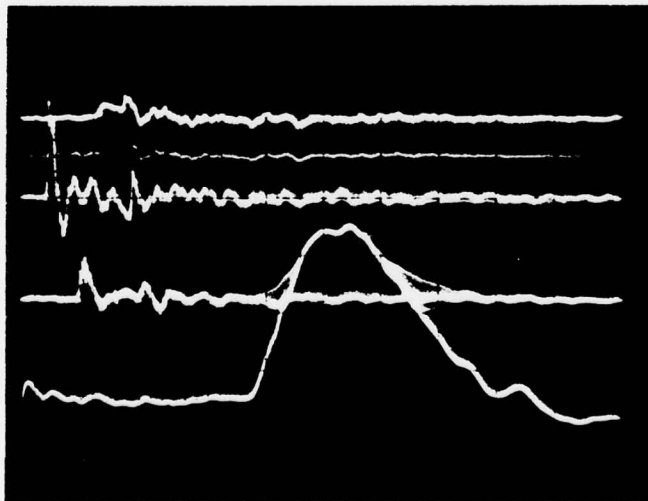
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>1</sub> Ch. 4 0.20V/div

Time Scale 10msec/div

Sustainer Voltage 25.8kV

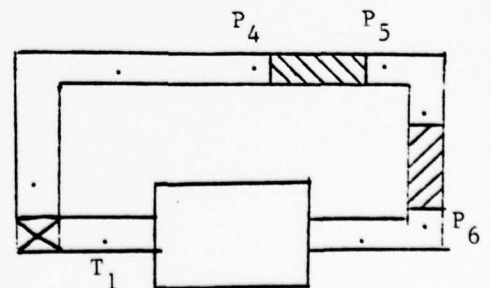
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: Preston amp set on  
100Hz bandwidth

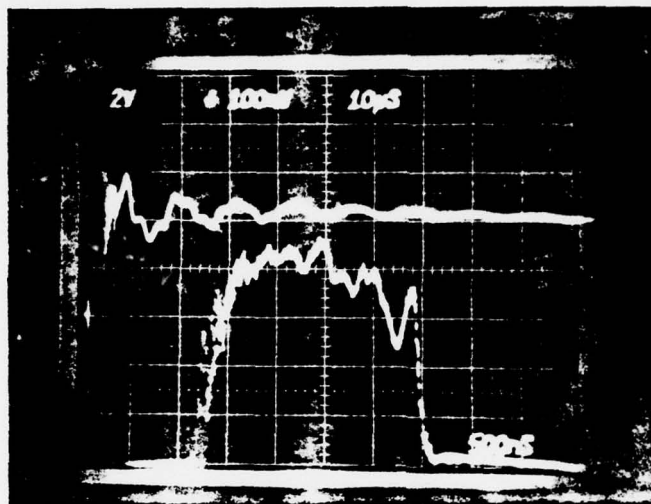
Analyzed Data:

$$E = 60.84$$



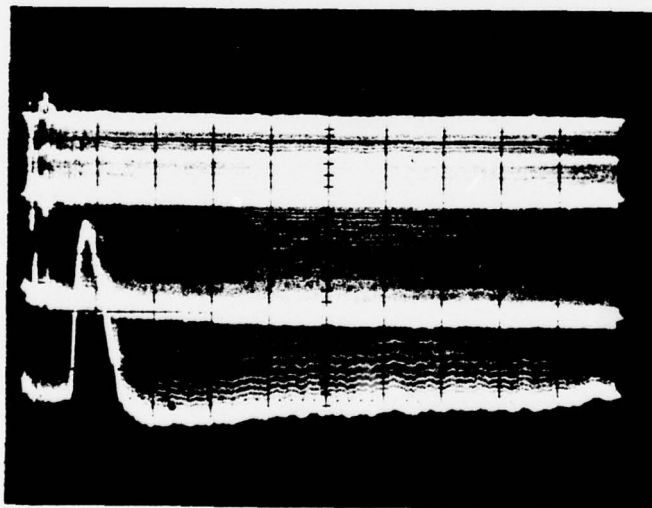
PVC Circulator Experimental Data

Page 189  
No. 5470  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



Voltages

P<sub>1</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5A</sub> Ch. 3 0.02V/div  
T<sub>1</sub> Ch. 4 0.20V/div

Time Scale 50msec/div  
Sustainer Voltage 25.8kV

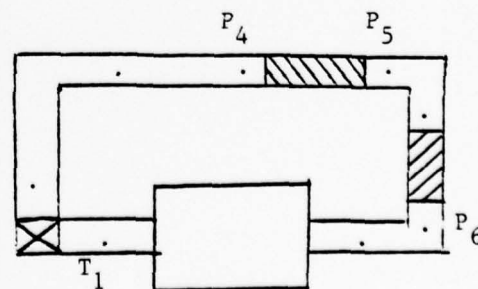
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: Preston amp on

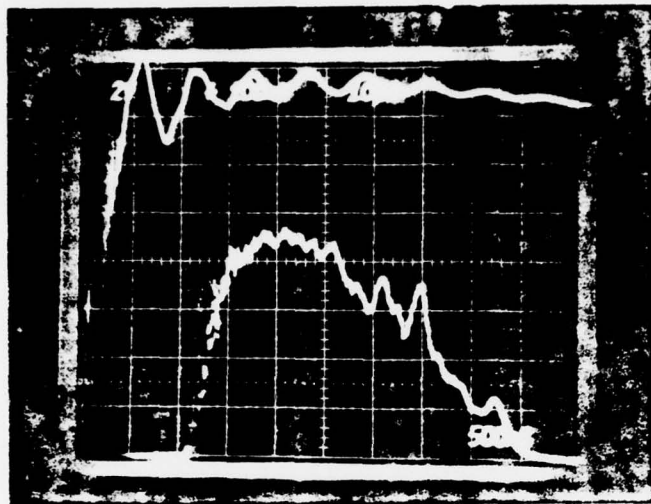
Analyzed Data:

$$E = 55.77$$



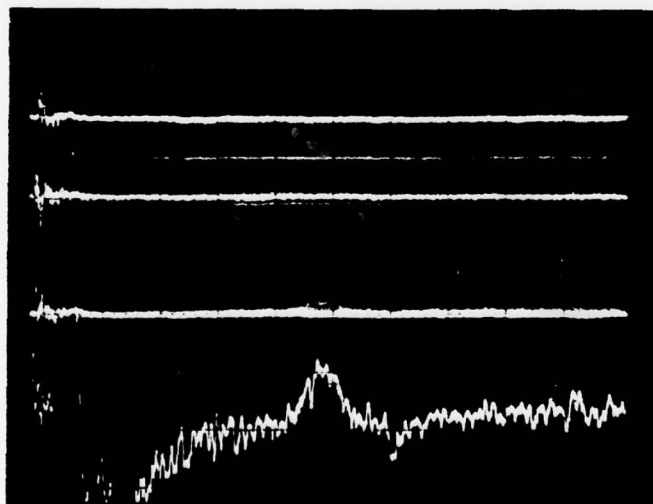
PVC Circulator Experimental Data

Page 191  
No. 5472  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10μsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



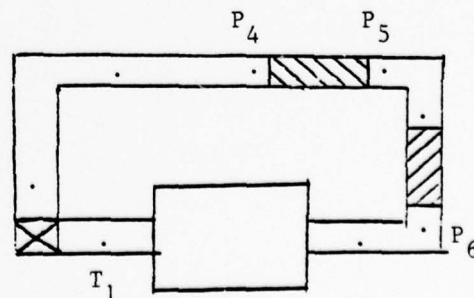
Voltages

- P Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T Ch. 4 0.05V/div

Time Scale .1sec/div  
Sustainer Voltage 25.8kV  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: \_\_\_\_\_

Analyzed Data:

$$E = 67.6$$

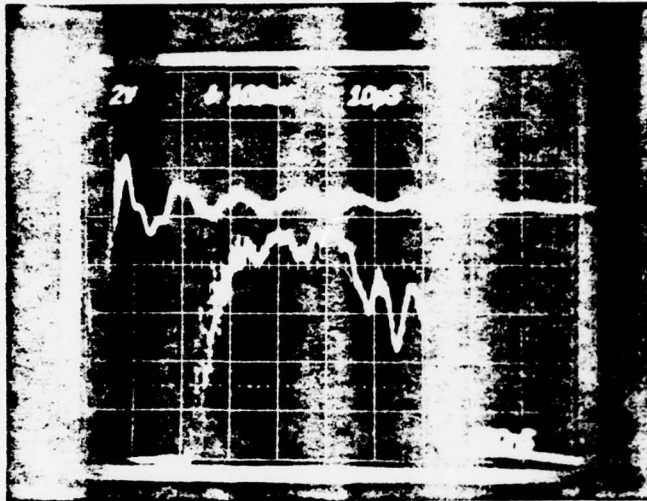


PVC Circulator Experimental Data

Page 192

No. 5473

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10µsec/div

Inverted? (Yes) No

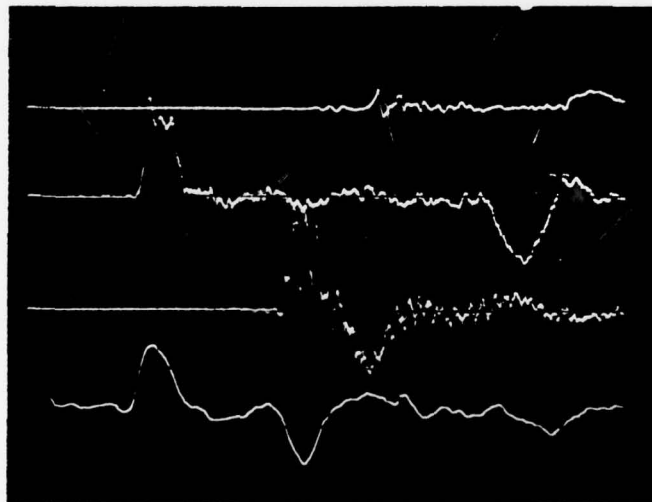
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>1</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

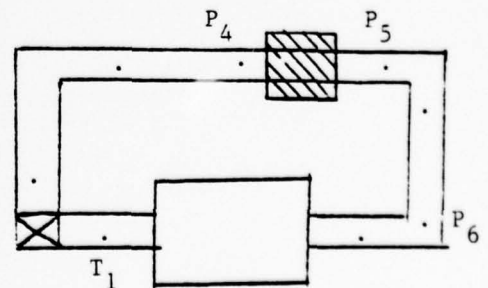
Flow? On Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

Analyzed Data:

$$E = 60.84$$



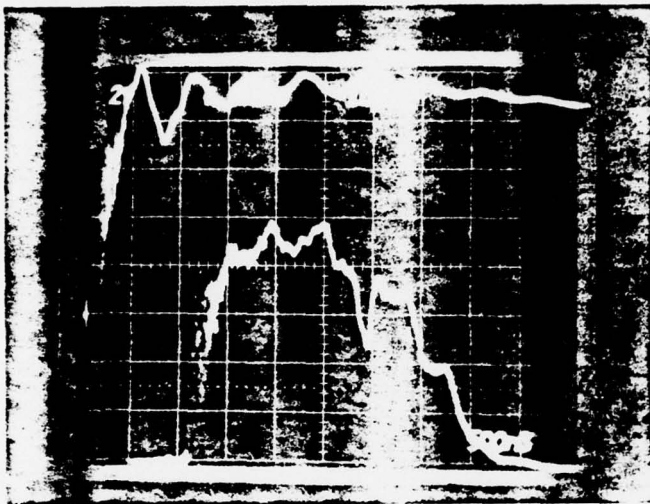


PVC Circulator Experimental Data

Page 193

No. 5474

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10usec/div

Inverted? (Yes) No

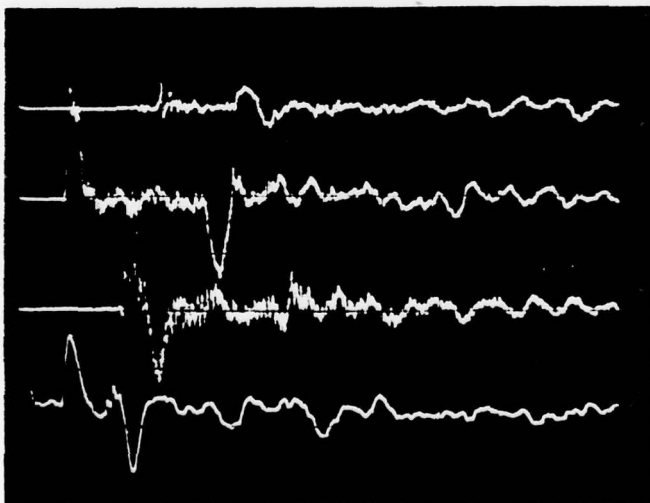
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>1</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

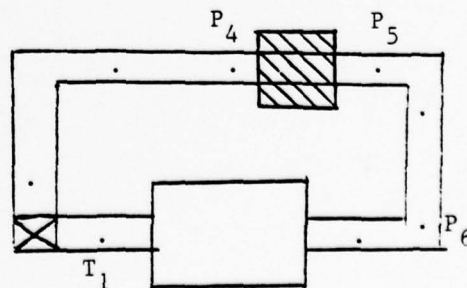
Flow? On Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

Analyzed Data:

$$E = 67.6$$

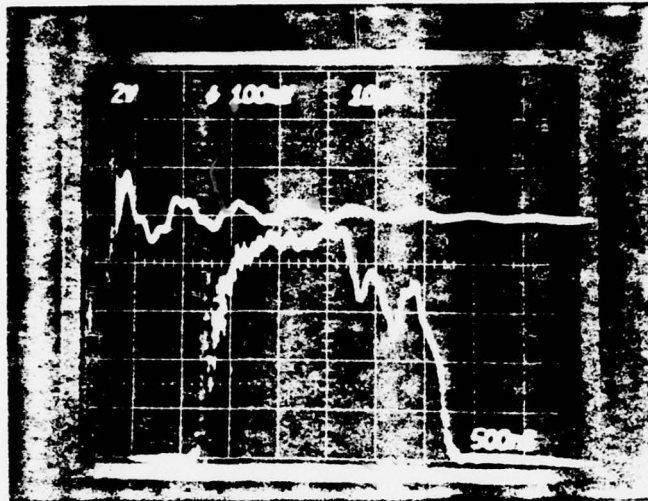


PVC Circulator Experimental Data

Page 194

No. 5475

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10nsec/div

Inverted? (Yes) No

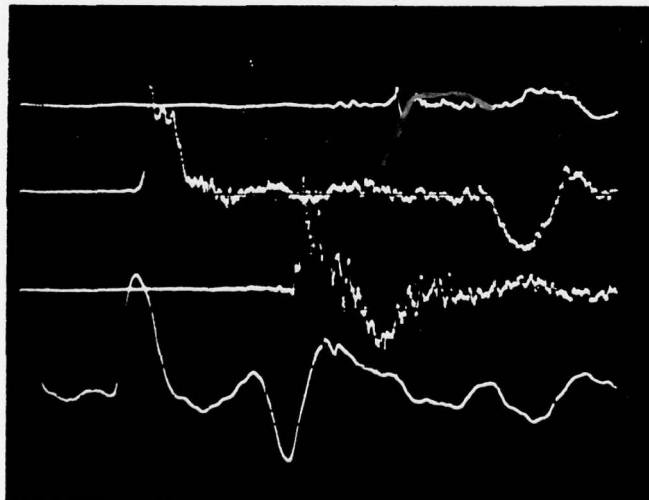
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>1</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

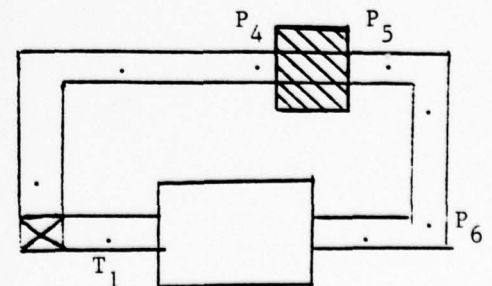
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

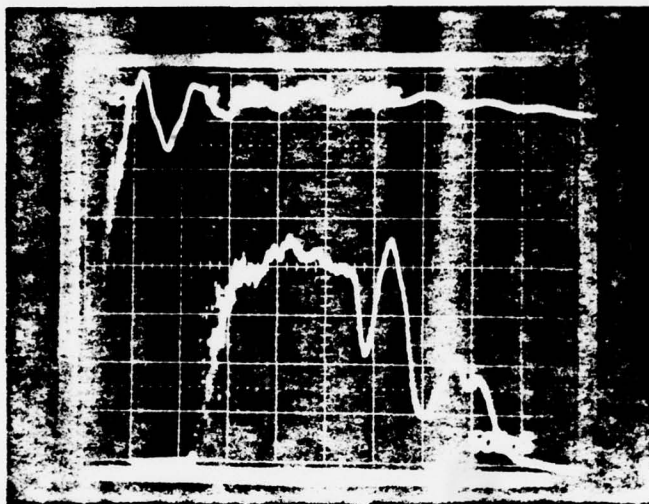
Analyzed Data:

$$E = 62.53$$



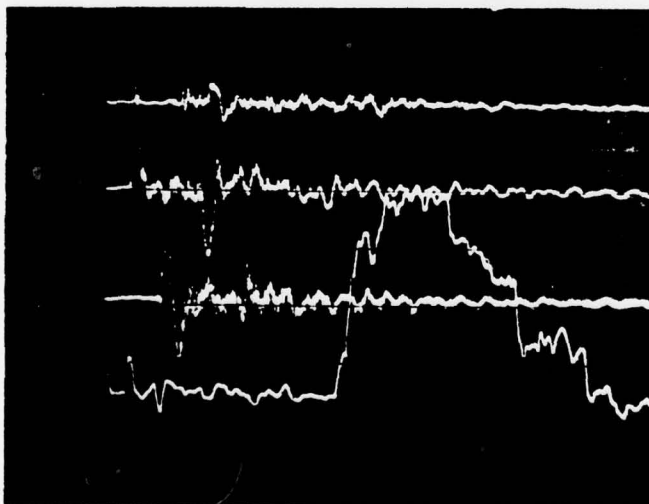
PVC Circulator Experimental Data

Page 195  
No. 5476  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10μsec/div  
Inverted? ☒ Yes ☐ No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes ☐ No ☒  
Attenuation



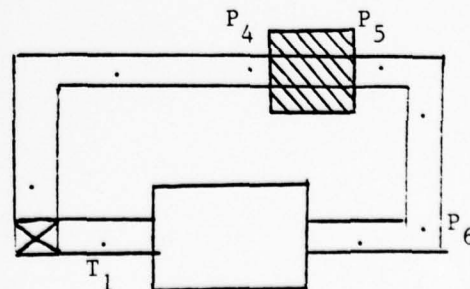
Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>1</sub> Ch. 4 0.20V/div

Time Scale 10msec/div  
Sustainer Voltage 25.8kV  
Flow? ☒ On ☐ Off  
Gas Type N<sub>2</sub>  
Notes: Horn muffler

Analyzed Data:

$$E = 64.22$$

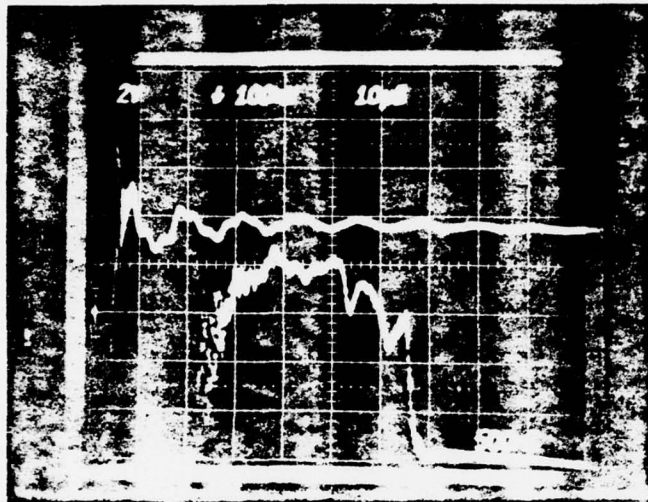


PVC Circulator Experimental Data

Page 196

No. 5477

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10μsec/div

Inverted? Yes No

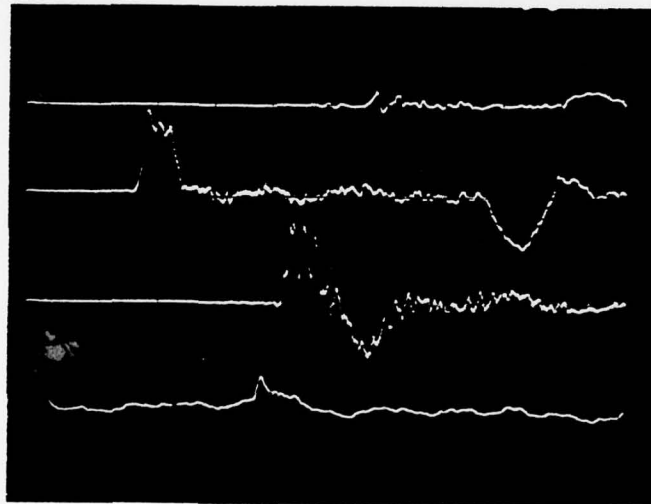
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes No

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>2</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

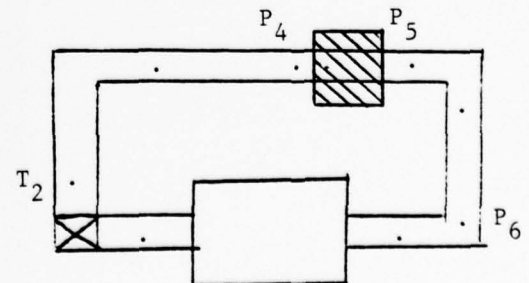
Flow? On Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

Analyzed Data:

$$E = 46.475$$



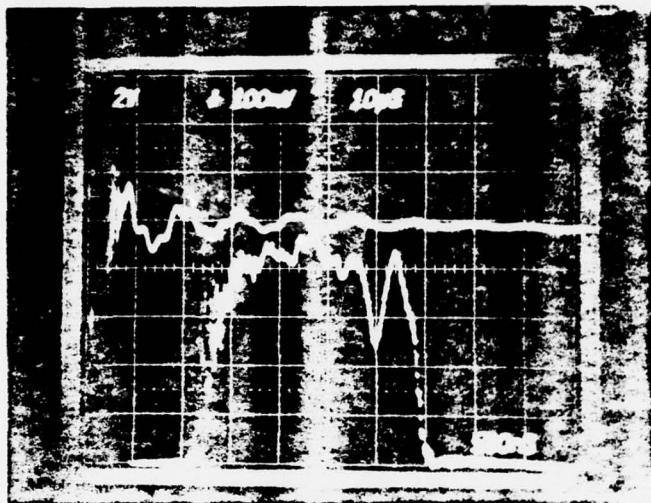


PVC Circulator Experimental Data

Page 197

No. 5478

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10nsec/div

Inverted? (Yes) No

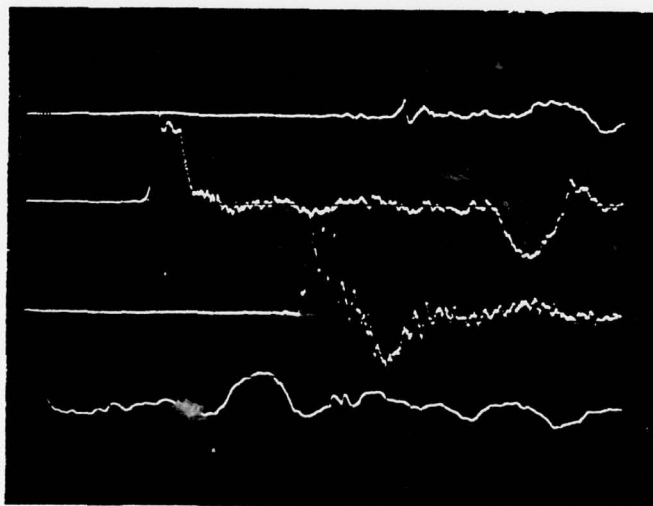
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>2</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

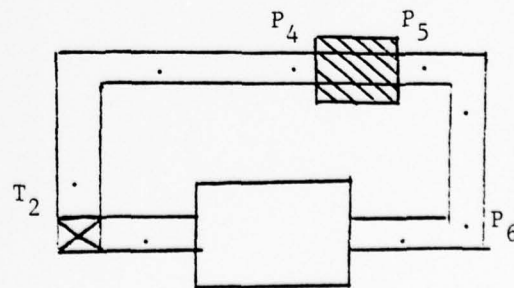
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

Analyzed Data:

$$E = 60.84$$



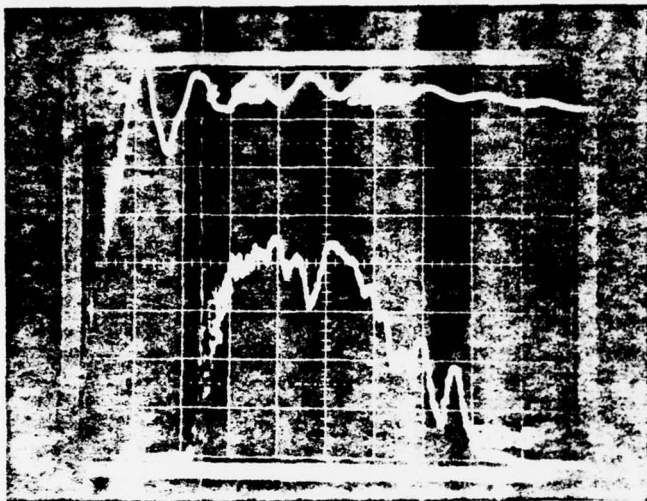


PVC Circulator Experimental Data

Page 198

No. 5479

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 1mV/div

Time Scale 10μsec/div

Inverted? (Yes) No

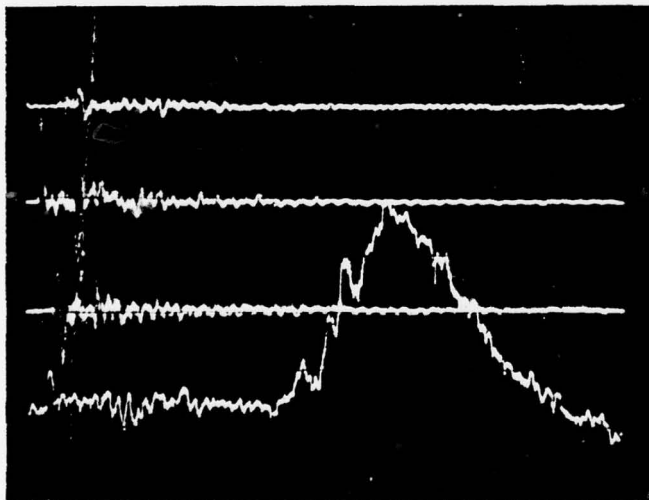
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>2</sub> Ch. 4 0.05V/div

Time Scale 20msec/div

Sustainer Voltage 25.8kV

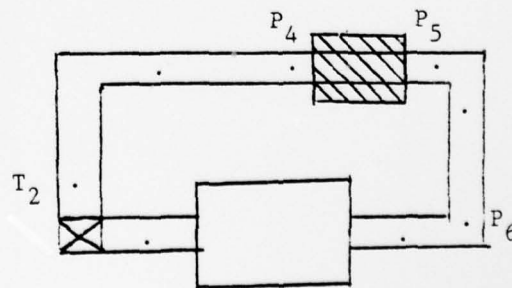
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

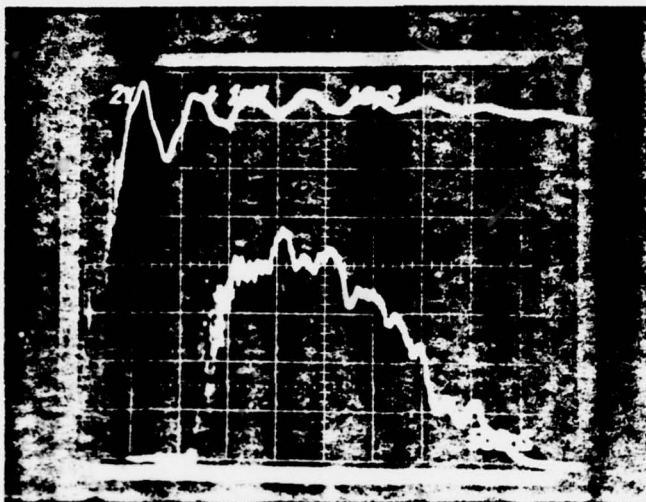
Analyzed Data:

E = 59.15



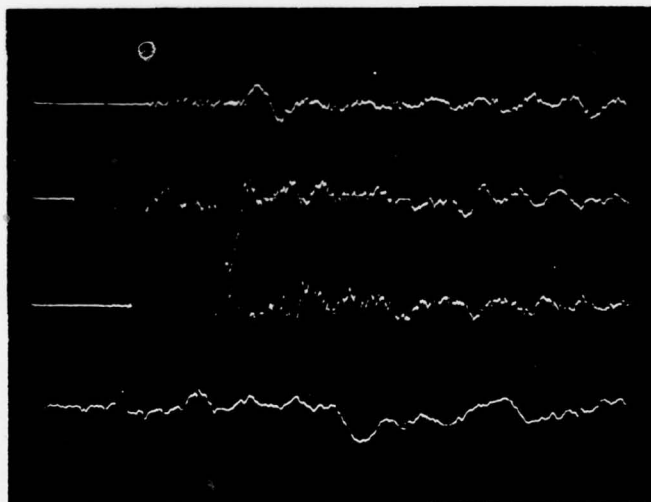
PVC Circulator Experimental Data

Page 199  
No. 5480  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 1mV/div  
Time Scale 10μsec/div  
Inverted? Yes No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes No  
Attenuation \_\_\_\_\_



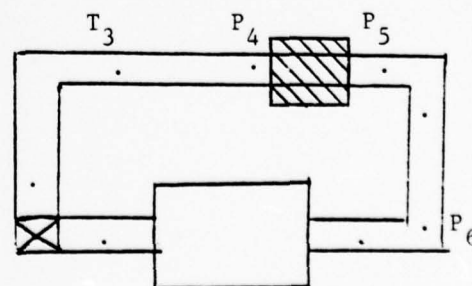
Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 5msec/div  
Sustainer Voltage 25.8kV  
Flow? On Off  
Gas Type N<sub>2</sub>  
Notes: Horn muffler

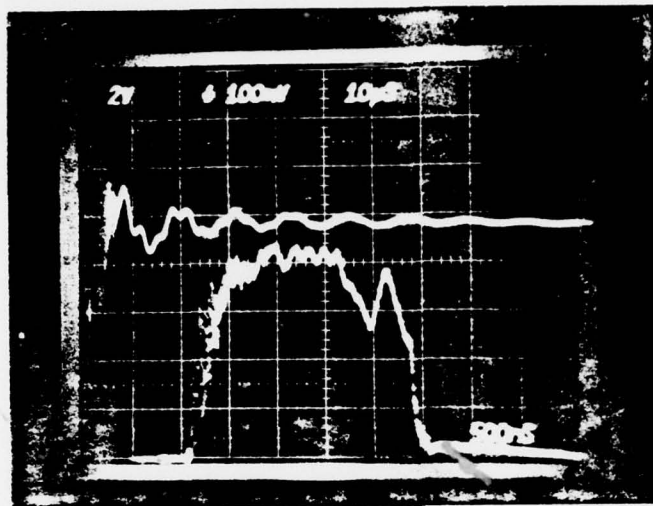
Analyzed Data:

$$E = 59.15$$



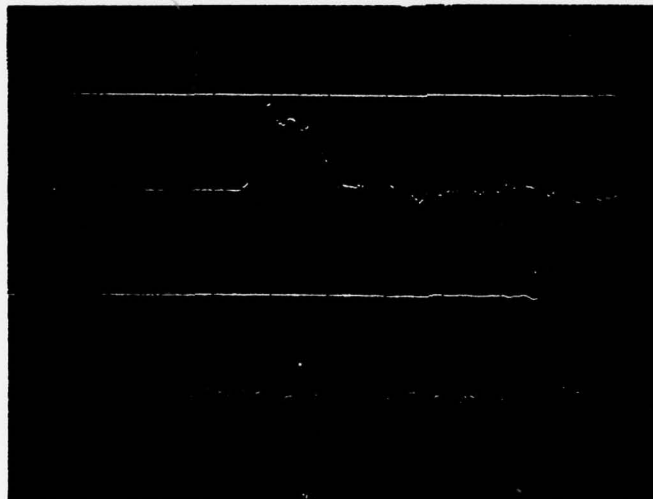
PVC Circulator Experimental Data

Page 200  
No. 5481  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10usec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V /div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



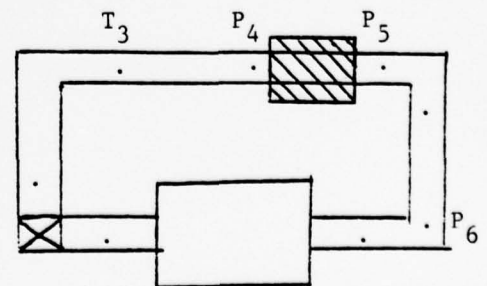
Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>3</sub> Ch. 4 0.05V/div

Time Scale .1msec/div  
Sustainer Voltage 25.8kV  
Flow? On (Off)  
Gas Type N<sub>2</sub>  
Notes: Horn muffler

Analyzed Data:

$$E = 55.77$$

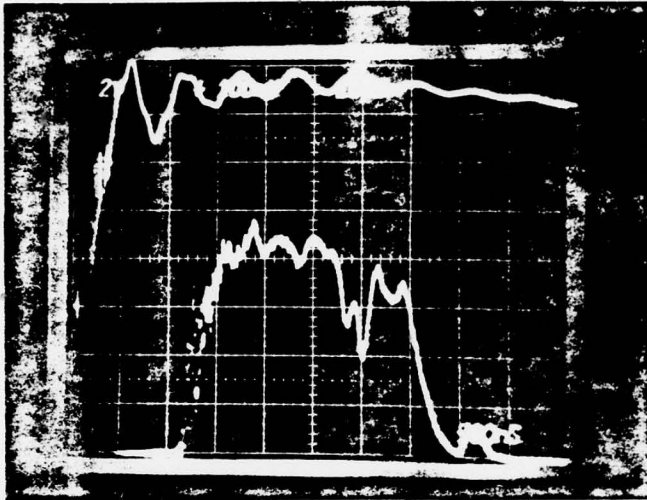


PVC Circulator Experimental Data

Page 201

No. 5482

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10μsec/div

Inverted? (Yes) No

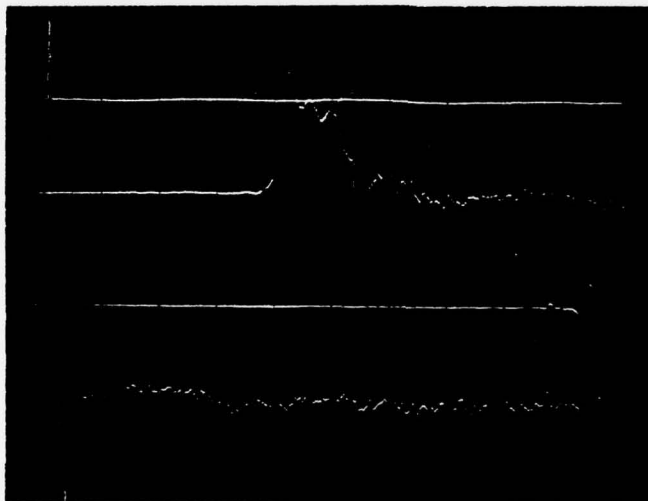
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 1msec/div

Sustainer Voltage 25.8kV

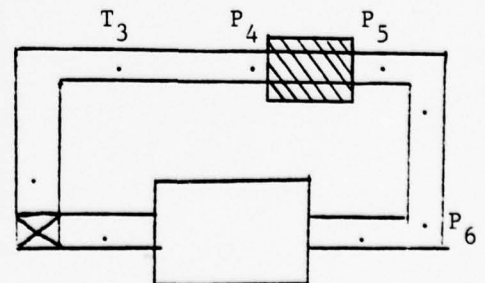
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

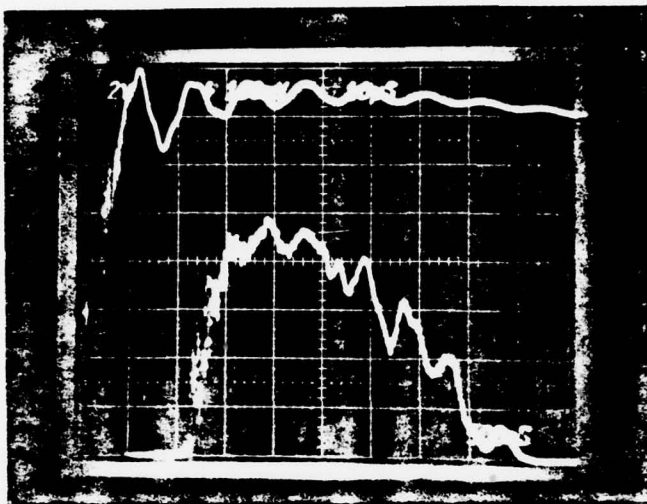
Analyzed Data:

$$E = 59.15$$



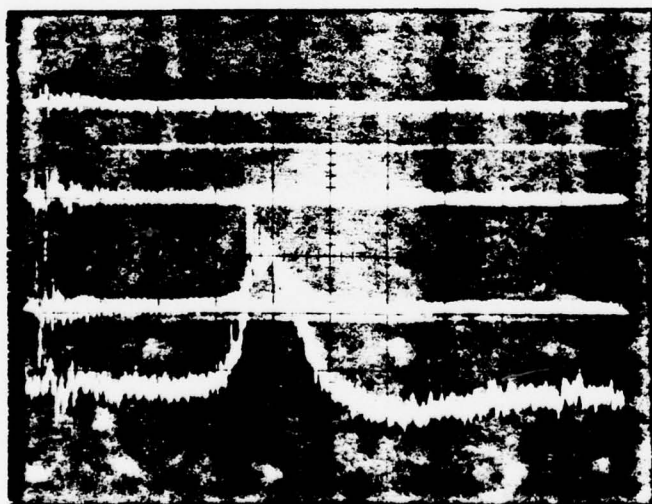
PVC Circulator Experimental Data

Page 202  
No. 5483  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10ns/div  
Inverted? Yes No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500ns/div  
Inverted? Yes No  
Attenuation \_\_\_\_\_



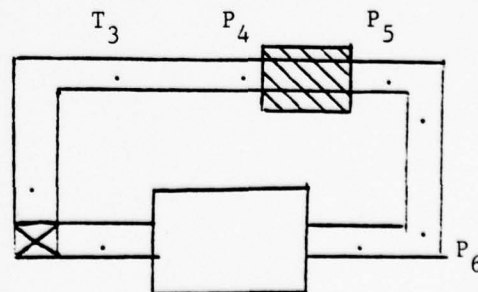
Voltages

P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>6</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>3</sub> Ch. 4 0.05V/div

Time Scale 50msec/div  
Sustainer Voltage 25.8kV  
Flow? On Off  
Gas Type N<sub>2</sub>  
Notes: Horn muffler

Analyzed Data:

$$E = 66.755$$



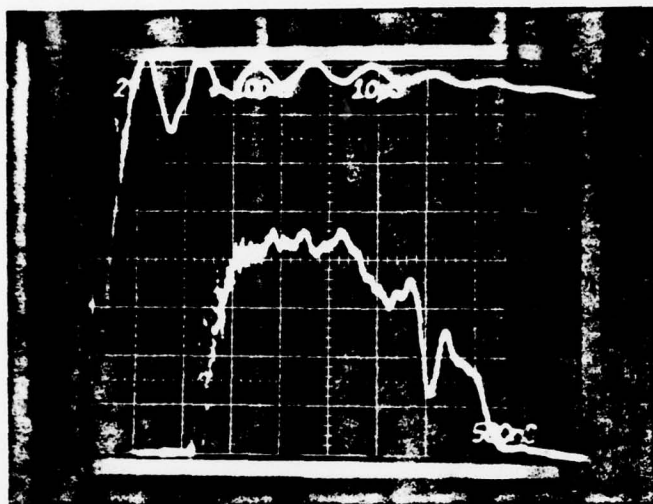


PVC Circulator Experimental Data

Page 203

No. 5484

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10μsec/div

Inverted? (Yes) No

2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>4</sub> Ch. 4 0.05V/div

Time Scale 50msec/div

Sustainer Voltage 25.8kV

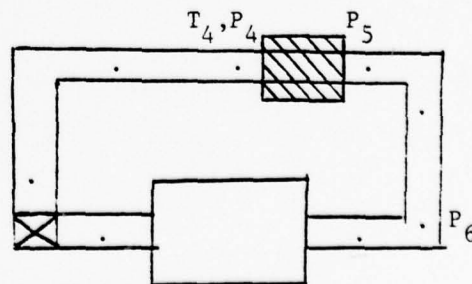
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

Analyzed Data:

$$E = 65.91$$

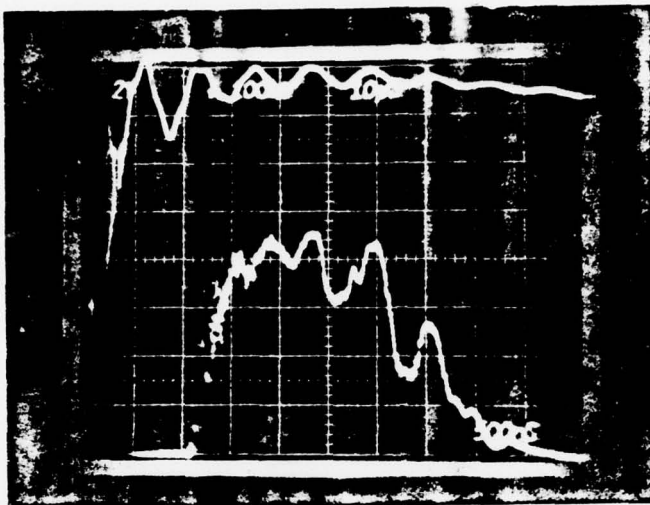


PVC Circulator Experimental Data

Page 204

No. 5485

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10usec/div

Inverted? (Yes) No

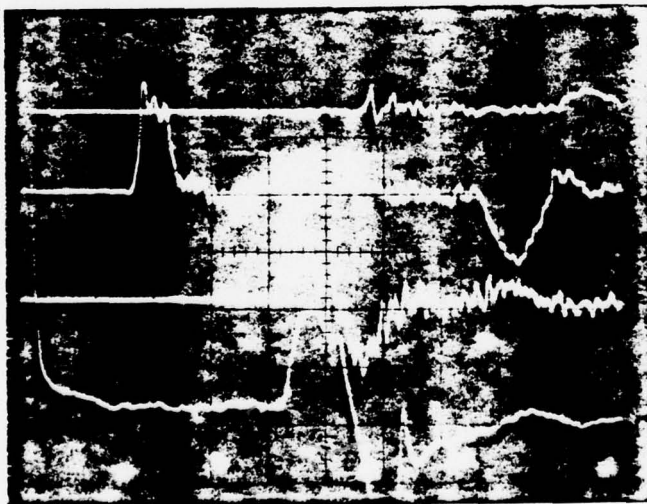
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.02V/div

Time Scale 2msec /div

Sustainer Voltage 25.8kV

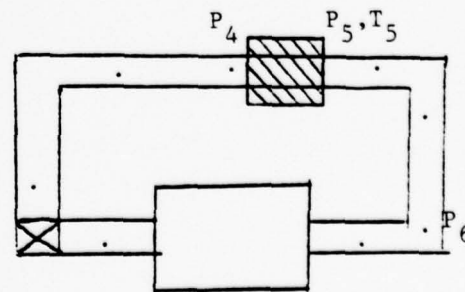
Flow? On Off

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 60.84$$

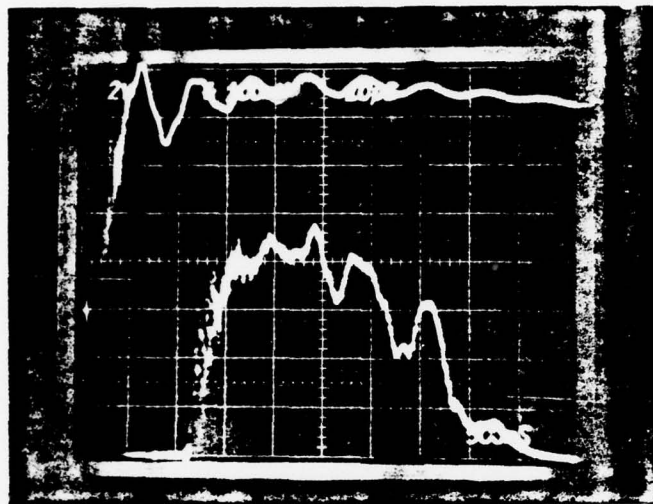


PVC Circulator Experimental Data

Page 205

No. 5486

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10μsec/div

Inverted? (Yes) No

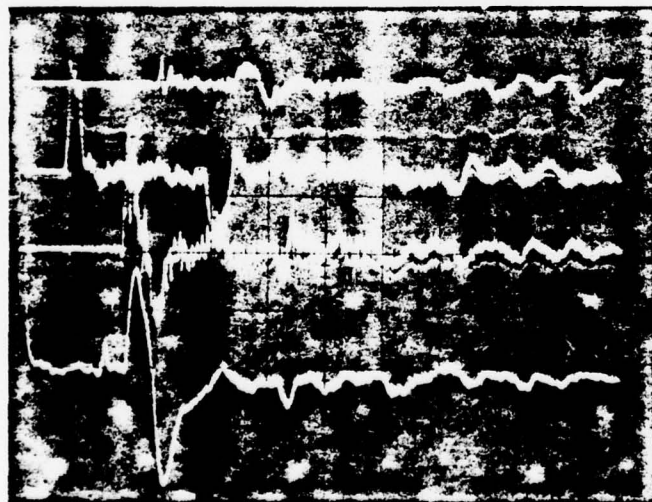
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

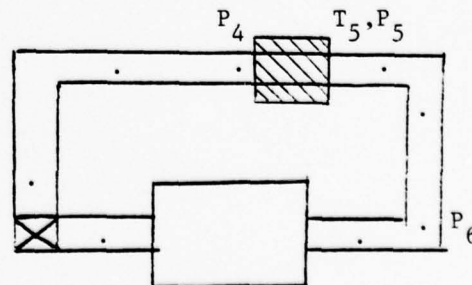
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: Horn muffler

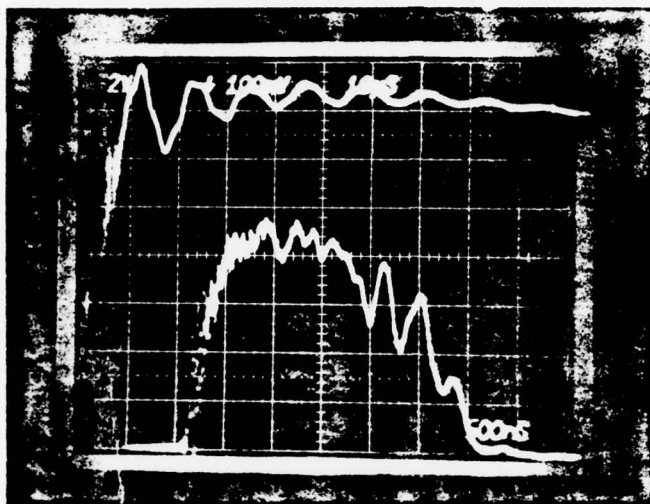
Analyzed Data:

$$E = 64.22$$



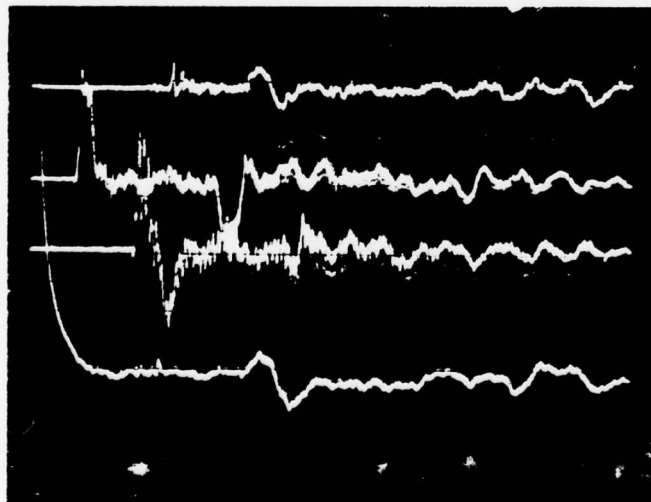
PVC Circulator Experimental Data

Page 206  
No. 5491  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10usec/div  
Inverted? ☒ Yes ☐ No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes ☐ No ☒  
Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>6</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>4</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

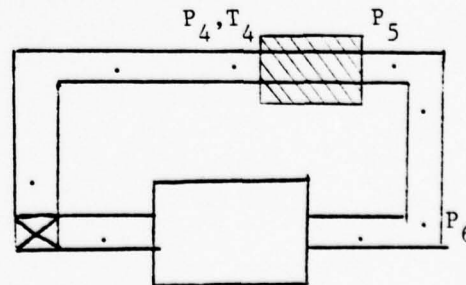
Flow? On ☒ Off ☐

Gas Type N<sub>2</sub>

Notes: \_\_\_\_\_

Analyzed Data:

$$E = 62.53$$



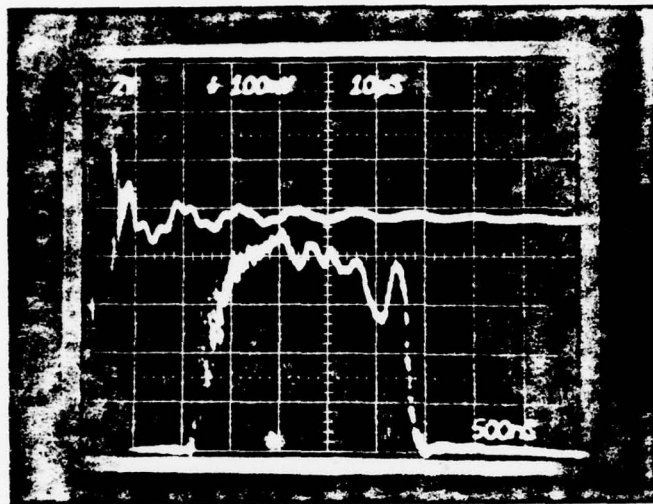


PVC Circulator Experimental Data

Page 207

No. 5492

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10μsec/div

Inverted? ☒ Yes ☐ No

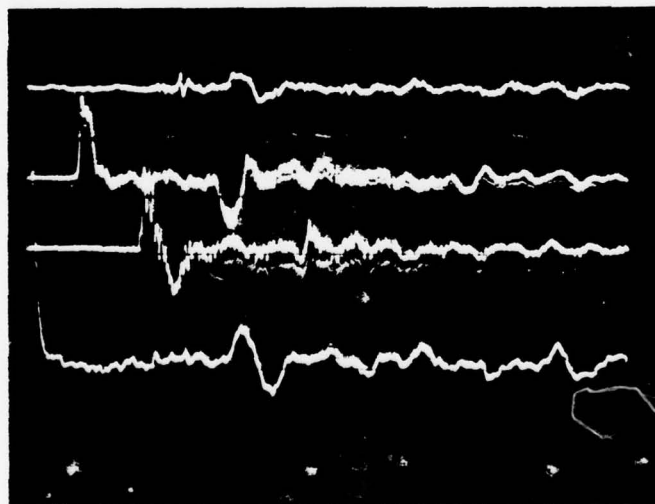
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes ☒ No ☐

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V /div

P<sub>6</sub> Ch. 2 0.02V /div

P<sub>5</sub> Ch. 3 0.02V /div

T<sub>4</sub> Ch. 4 0.05V /div

Time Scale 5msec /div

Sustainer Voltage 25.8kV

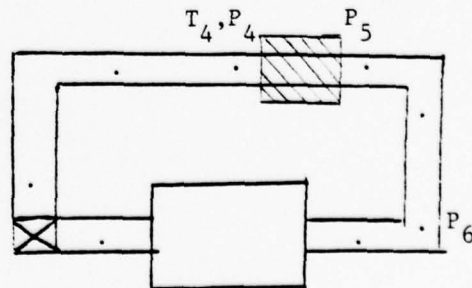
Flow? ☒ On ☐ Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

Analyzed Data:

E = 54.08



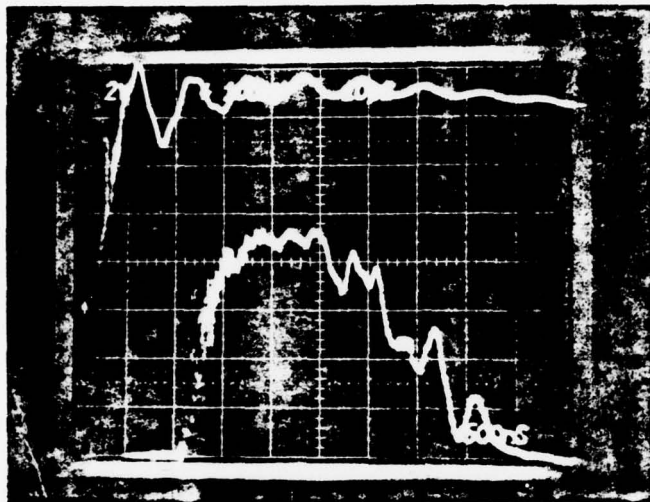


PVC Circulator Experimental Data

Page 208

No. 5493

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10nsec/div

Inverted? (Yes) No

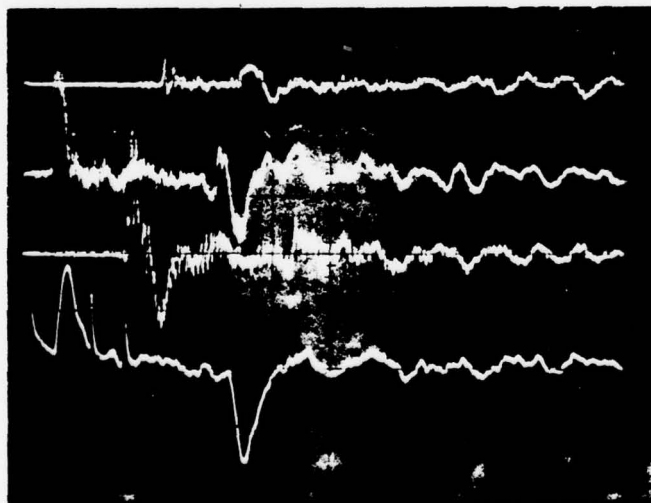
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>7</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>7</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

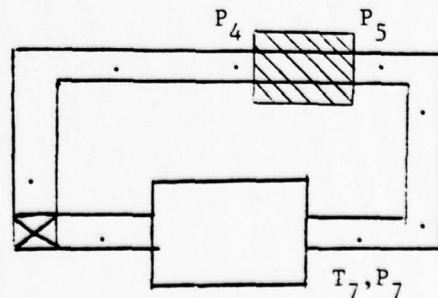
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: Horn muffler

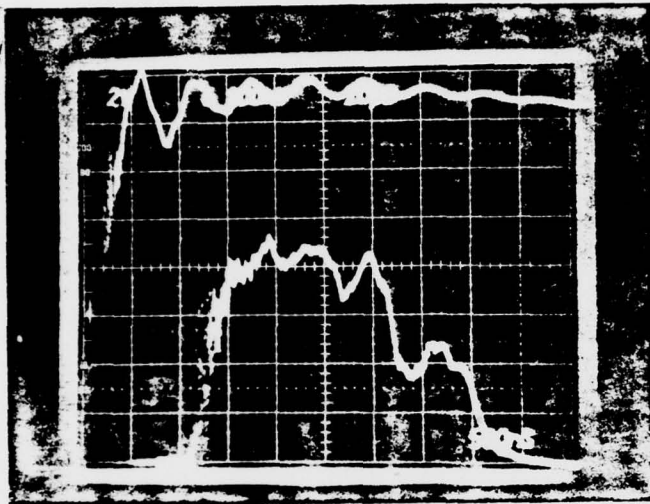
Analyzed Data:

$$E = 64.22$$



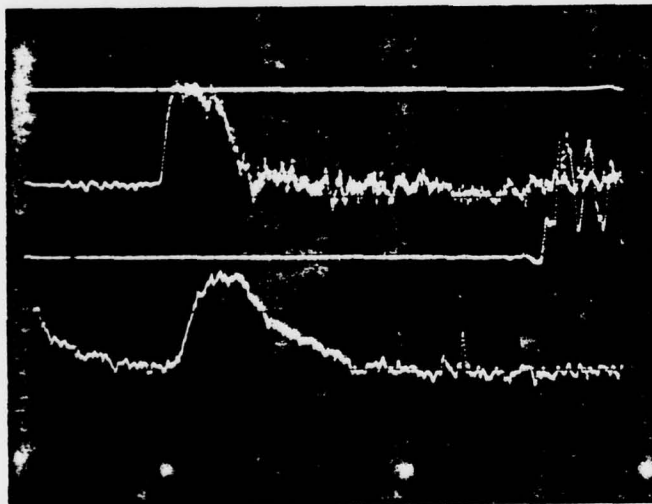
PVC Circulator Experimental Data

Page 209  
No. 5494  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10µsec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation \_\_\_\_\_



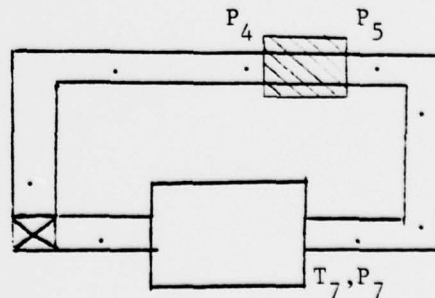
Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>7</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>7</sub> Ch. 4 0.05V/div

Time Scale 1msec/div  
Sustainer Voltage 25.8kV  
Flow? (On) Off  
Gas Type N<sub>2</sub>  
Notes: Horn muffler

Analyzed Data:

$$E = 64.22$$

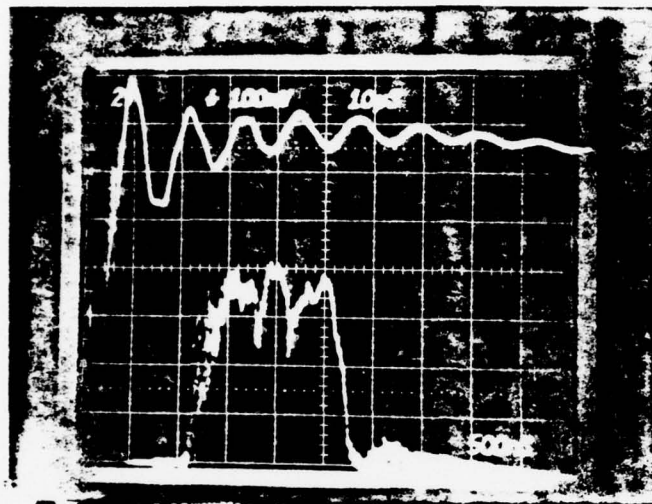


PVC Circulator Experimental Data

Page 210

No. 5496

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10μsec/div

Inverted? Yes No

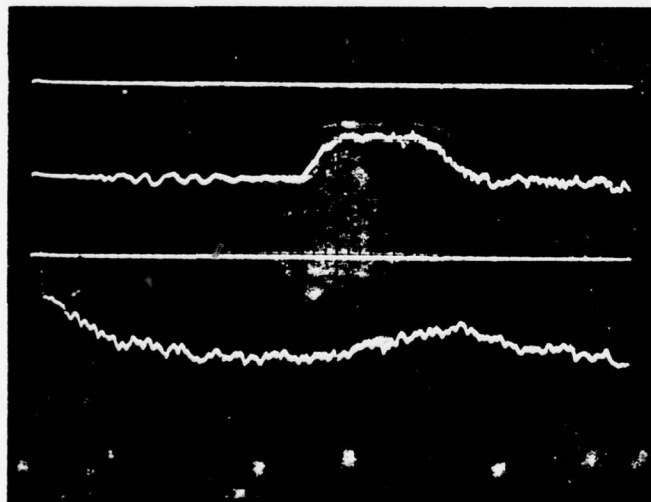
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes No

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>7</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>7</sub> Ch. 4 0.05V/div

Time Scale .5msec/div

Sustainer Voltage 25.8kV

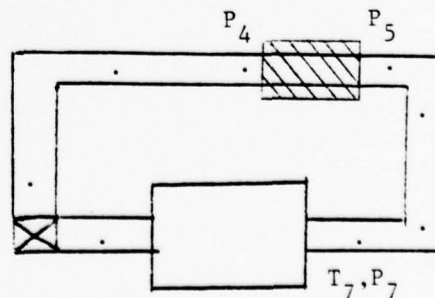
Flow? On Off

Gas Type N<sub>2</sub>

Notes:           

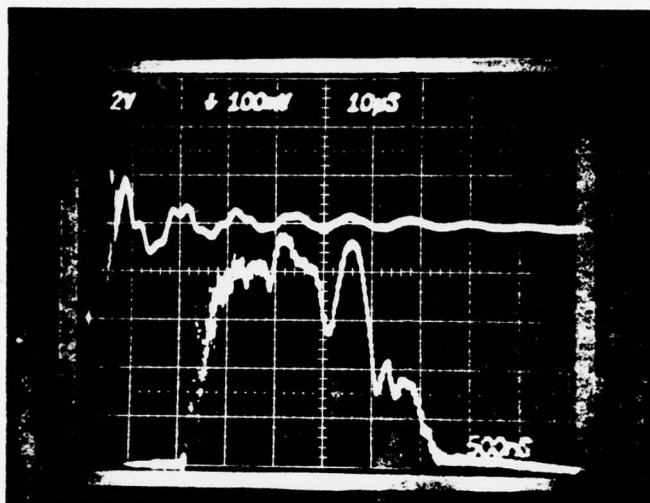
Analyzed Data:

E = 33.80



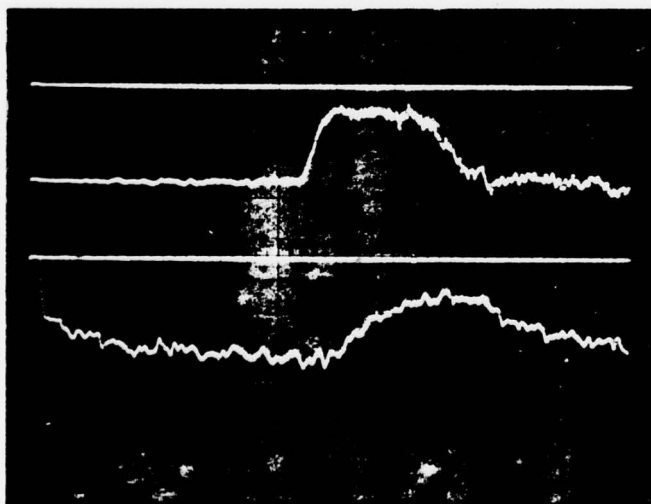
# PVC Circulator Experimental Data

Page 211  
No. 5497  
Date 12 July 1978



## Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10usec/div  
Inverted? ☒ Yes ☐ No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes ☐ No ☒  
Attenuation \_\_\_\_\_

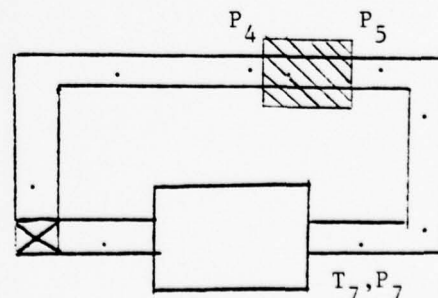


## Voltages

P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>7</sub> Ch. 2 0.02V/div  
P<sub>5</sub> Ch. 3 0.02V/div  
T<sub>7</sub> Ch. 4 0.05V/div  
Time Scale .5msec/div  
Sustainer Voltage 25.8kV  
Flow? On ☐ Off ☒  
Gas Type N<sub>2</sub>  
Notes: Horn muffler

## Analyzed Data:

E = 54.08

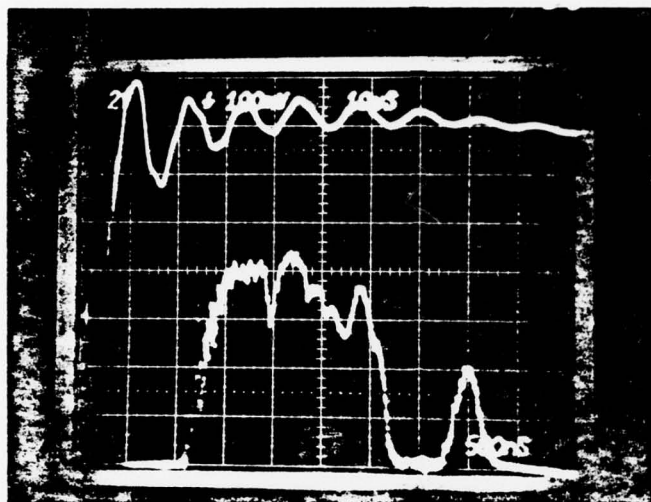


PVC Circulator Experimental Data

Page 212

No. 5498

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10usec/div

Inverted? (Yes) No

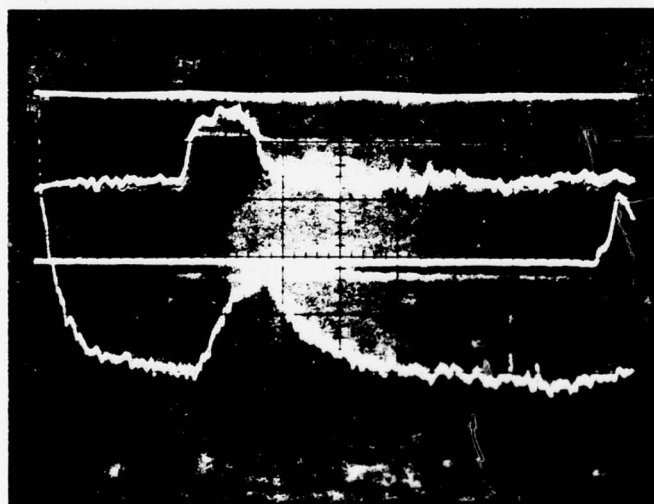
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V /div

P<sub>7</sub> Ch. 2 0.02V /div

P<sub>5</sub> Ch. 3 0.02V /div

T<sub>7</sub> Ch. 4 0.05V /div

Time Scale 1msec /div

Sustainer Voltage 25.8kV

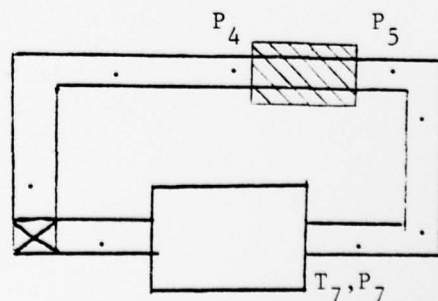
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: Horn muffler

Analyzed Data:

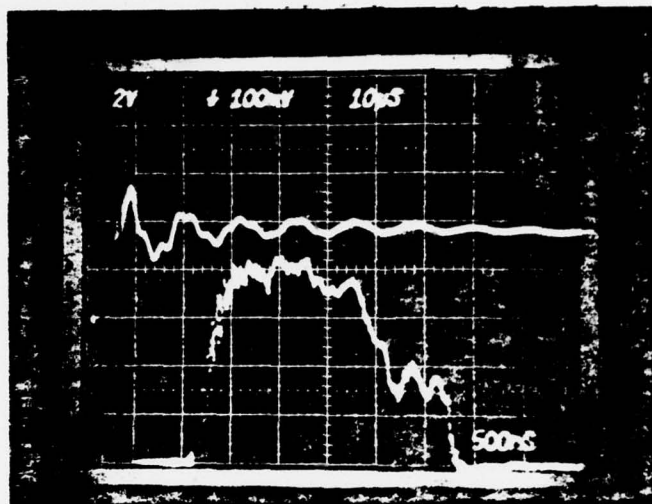
$$E = 50.70$$





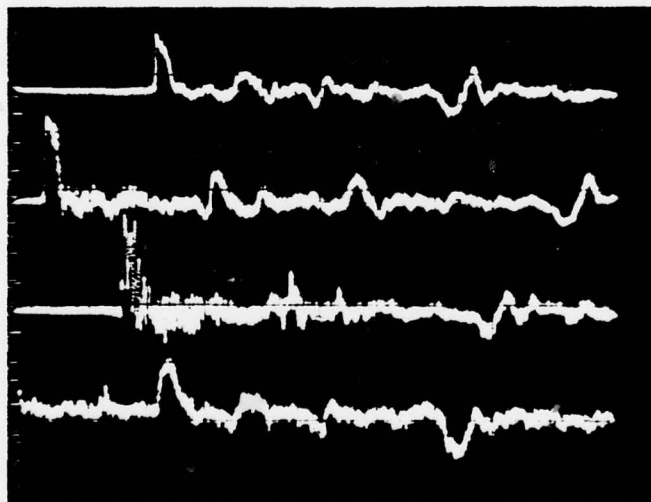
PVC Circulator Experimental Data

Page 213  
 No. 5500  
 Date 12 July 1978



Gun Data

1. Upper Trace  
 Voltage 100mV/div  
 Time Scale 10μsec/div  
 Inverted? Yes No
2. Lower Trace  
 Voltage 2V/div  
 Time Scale 500nsec/div  
 Inverted? Yes No  
 Attenuation \_\_\_\_\_



Voltages

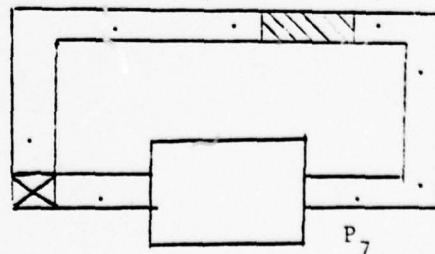
- P<sub>4</sub> Ch. 1 0.02V/div  
 P<sub>7</sub> Ch. 2 0.02V/div  
 P<sub>5</sub> Ch. 3 0.02V/div  
 T<sub>4</sub> Ch. 4 0.05V/div  
 Time Scale 5msec/div  
 Sustainer Voltage 25.8kV  
 Flow? On Off  
 Gas Type N<sub>2</sub>

Notes: 12-1" honeycomb  
 sections (6 coarse + 6  
 fine) 1 KHz low pass  
 filter

P<sub>4</sub>, T<sub>4</sub> P<sub>5</sub>

Analyzed Data:

$$E = 54.08$$

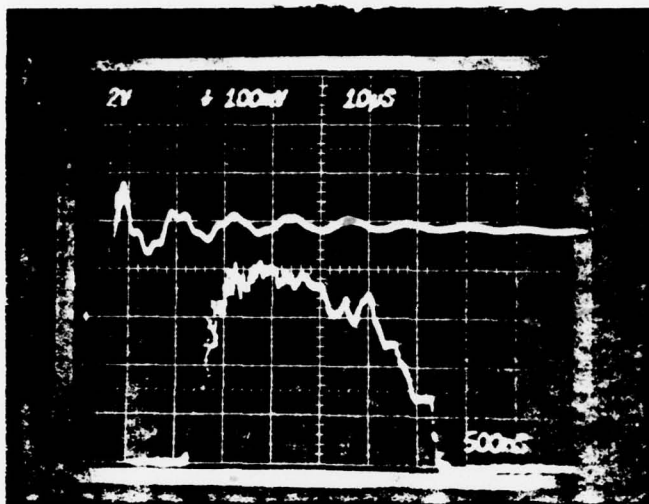


PVC Circulator Experimental Data

Page 214

No. 5501

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10µsec/div

Inverted? (Yes) No

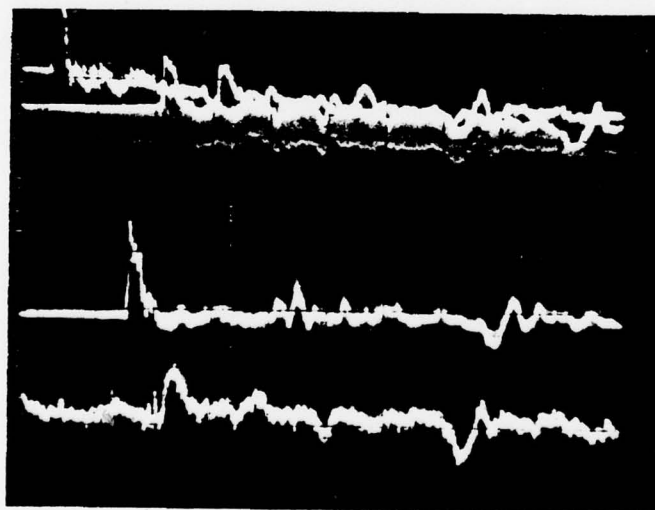
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>7</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>4</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

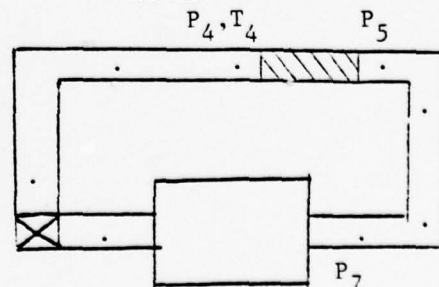
Flow? On (Off)

Gas Type N<sub>2</sub>

Notes: 12-1" honeycomb  
sections (6 coarse +  
6 fine) 1 KH2 low pass  
filter

Analyzed Data:

E = 54.08

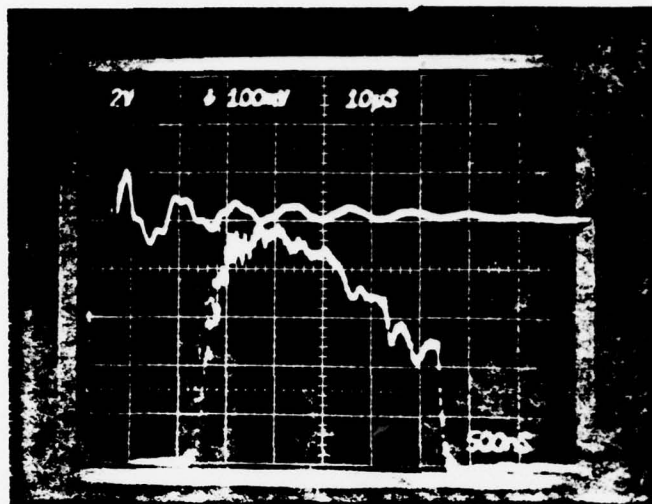


PVC Circulator Experimental Data

Page 215

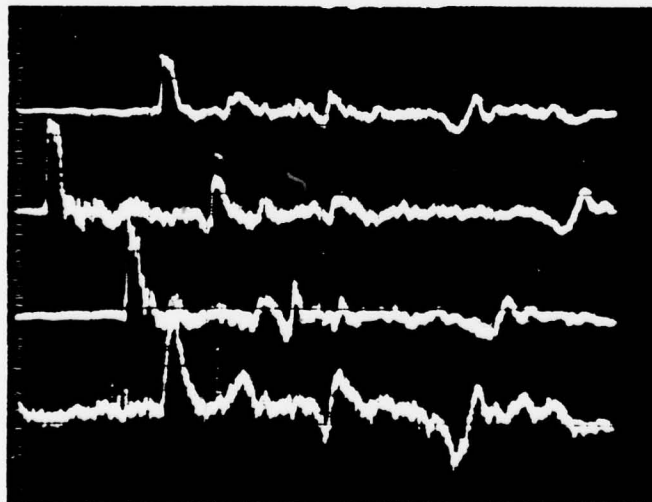
No. 5502

Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10usec/div  
Inverted? ☒ Yes ☐ No
2. Lower Trace  
Voltage 2V /div  
Time Scale 500nsec/div  
Inverted? Yes ☐ No ☒  
Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V /div

P<sub>7</sub> Ch. 2 0.02V /div

P<sub>5</sub> Ch. 3 0.02V /div

T<sub>4</sub> Ch. 4 0.05V /div

Time Scale 5msec /div

Sustainer Voltage 25.8kV

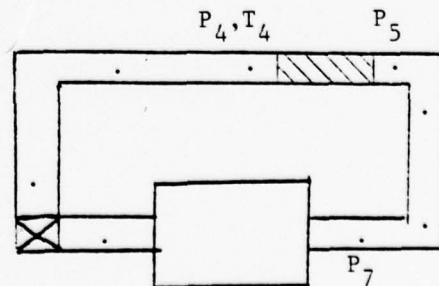
Flow? ☒ On ☐ Off

Gas Type N<sub>2</sub>

Notes: 12-1" honeycomb  
(6 coarse + 6 fine)  
1 KHz low pass filter

Analyzed Data:

$$E = 62.53$$

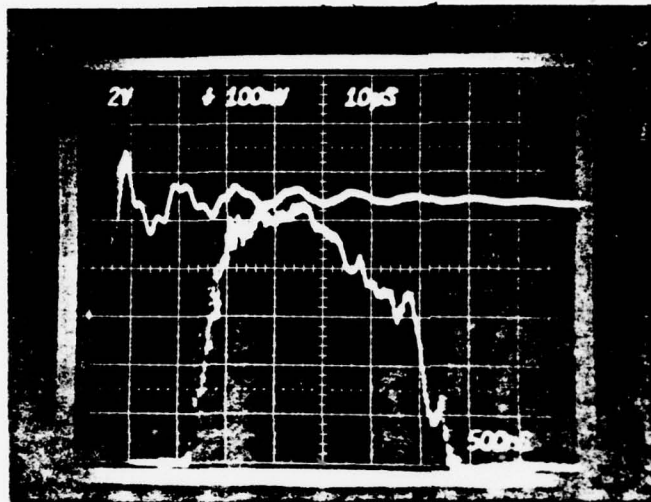


PVC Circulator Experimental Data

Page 216

No. 5503

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10usec/div

Inverted? ☒ Yes ☐ No

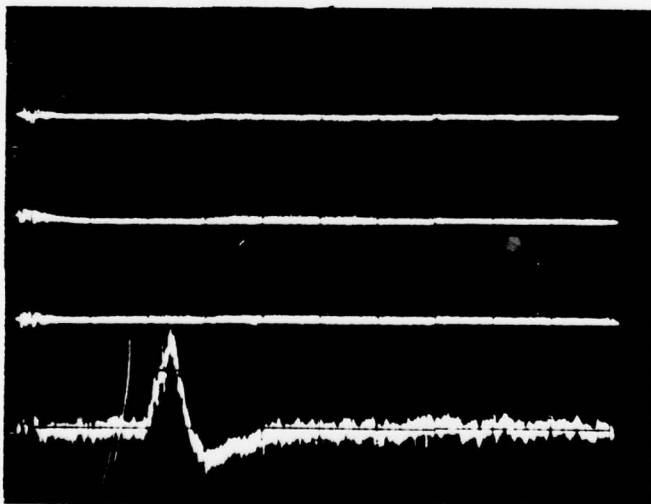
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes ☐ No ☒

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V /div

P<sub>7</sub> Ch. 2 0.02V /div

P<sub>5</sub> Ch. 3 0.02V /div

T<sub>4</sub> Ch. 4 0.05V /div

Time Scale 0.2sec/div

Sustainer Voltage 25.8kV

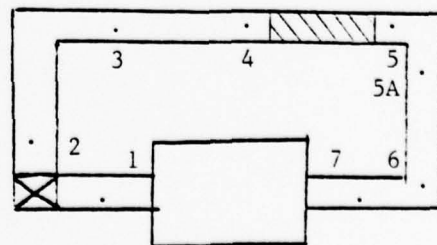
Flow? ☒ On ☐ Off

Gas Type N<sub>2</sub>

Notes: 12-1" honeycomb  
(6 coarse + 6 fine)  
1 KHz low pass filter

Analyzed Data:

$$E = 69.29$$

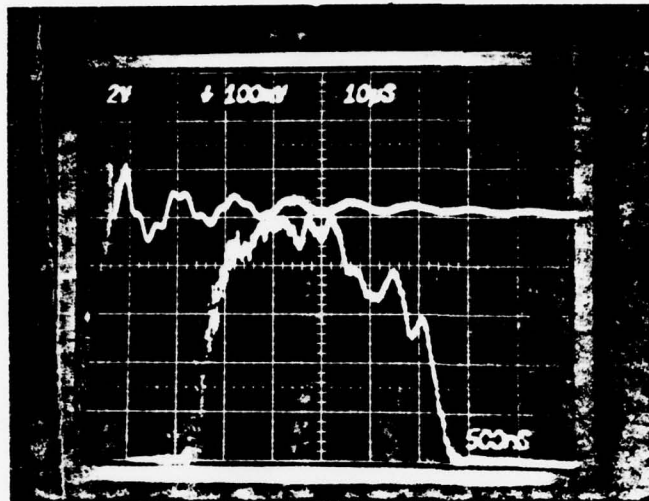


PVC Circulator Experimental Data

Page 217

No. 5504

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10μsec/div

Inverted? Yes No

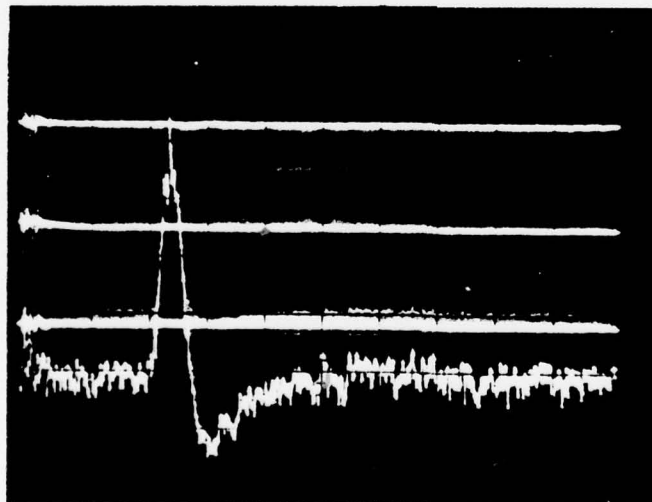
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes No

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V /div

P<sub>7</sub> Ch. 2 0.02V /div

P<sub>5</sub> Ch. 3 0.02V /div

T<sub>4</sub> Ch. 4 0.02V /div

Time Scale 0.2sec/div

Sustainer Voltage 25.8kV

Flow? On Off

Gas Type N<sub>2</sub>

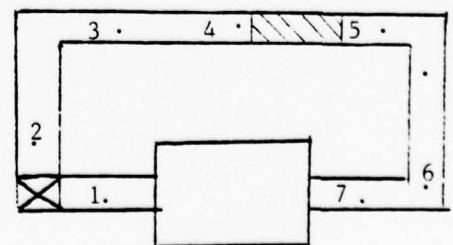
Notes: 12-1" honeycomb

(6 coarse + 6 fine)

100 Hz low pass filter

Analyzed Data:

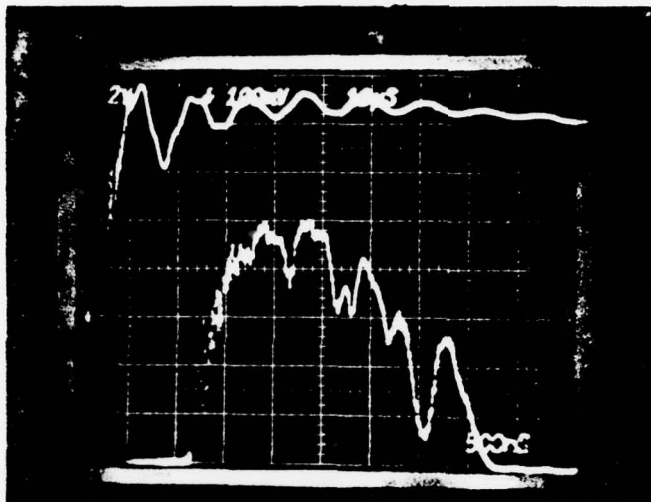
$$E = 70.135$$





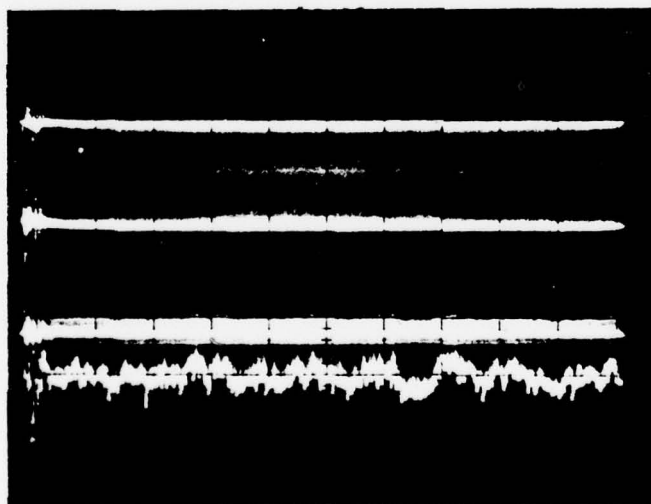
PVC Circulator Experimental Data

Page 218  
 No. 5505  
 Date 12 July 1978



Gun Data

1. Upper Trace  
 Voltage 100mV/div  
 Time Scale 10nsec/div  
 Inverted? (Yes) No
2. Lower Trace  
 Voltage 2V/div  
 Time Scale 500nsec/div  
 Inverted? Yes (No)  
 Attenuation \_\_\_\_\_



Voltages

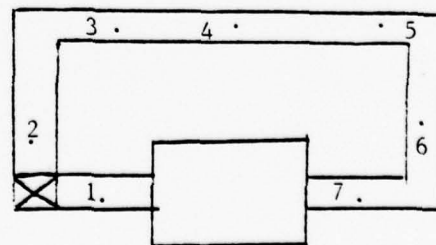
- P<sub>4</sub> Ch. 1 0.02V/div  
 P<sub>7</sub> Ch. 2 0.02V/div  
 P<sub>5</sub> Ch. 3 0.02V/div  
 T<sub>5</sub> Ch. 4 0.02V/div

Time Scale 0.2sec/div  
 Sustainer Voltage 25.8kV  
 Flow? (On) Off  
 Gas Type N<sub>2</sub>

Notes: 100 Hz bandwidth  
low pass filter 12-1"  
honeycomb (6 coarse +  
6 fine)

Analyzed Data:

$$E = 67.60$$

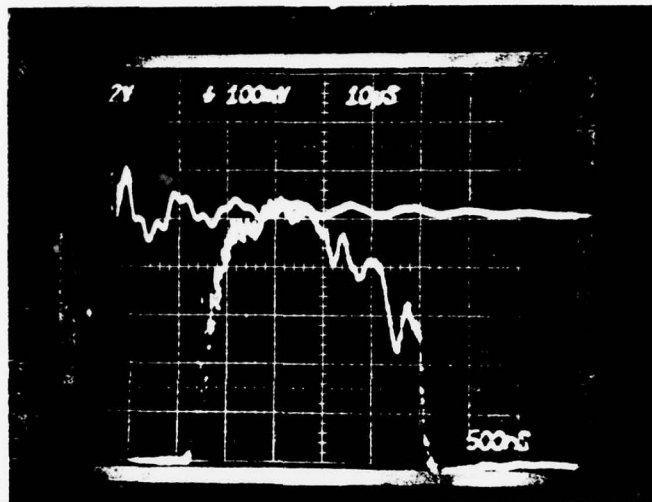


PVC Circulator Experimental Data

Page 219

No. 5506

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10nsec/div

Inverted? ☒ Yes ☐ No

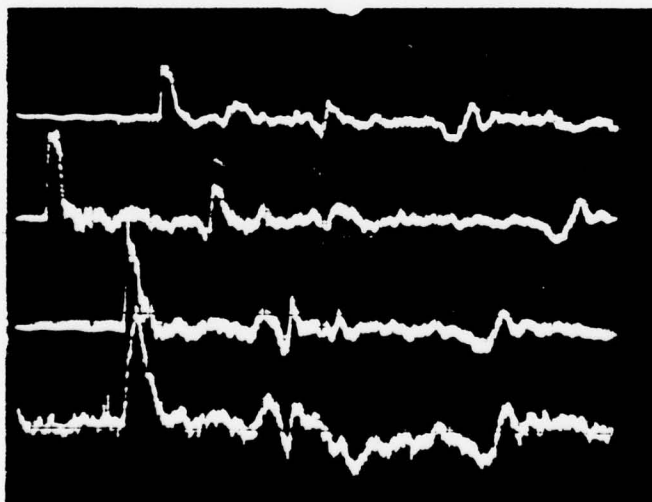
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes ☐ No ☒

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>7</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.05V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

Flow? ☒ On ☐ Off

Gas Type N<sub>2</sub>

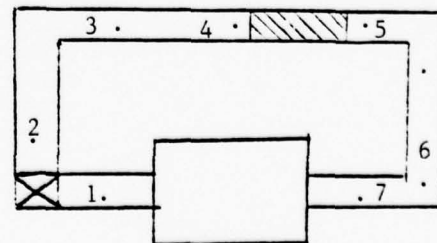
Notes: 12-1" honeycomb

(6 coarse + 6 fine)

1 KHz low pass filter

Analyzed Data:

$$E = 65.065$$

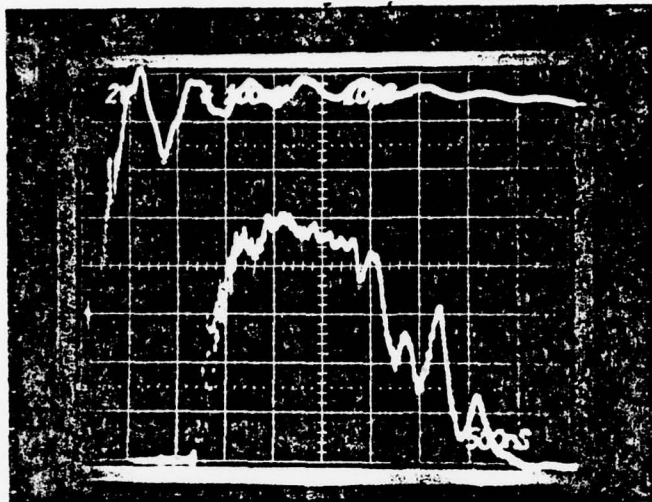


PVC Circulator Experimental Data

Page 220

No. 5507

Date 12 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10usec/div

Inverted? (Yes) No

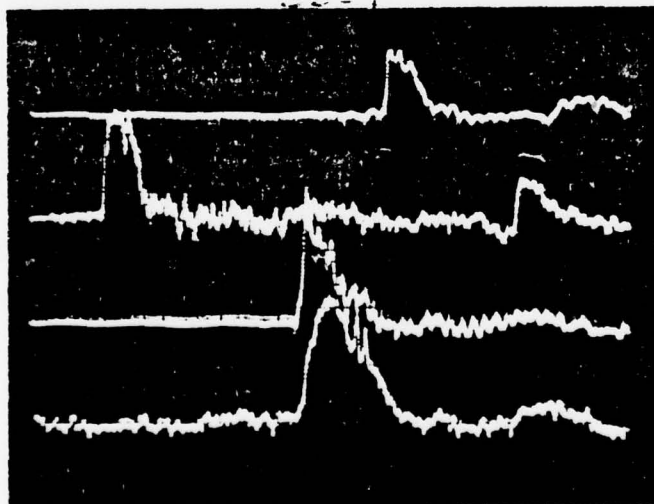
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>7</sub> Ch. 2 0.02V/div

P<sub>5</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.05V/div

Time Scale 2msec/div

Sustainer Voltage 25.8kV

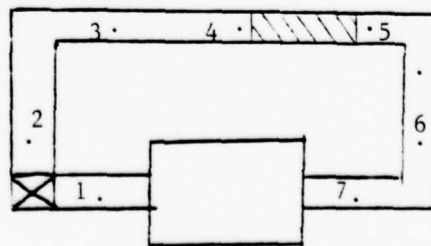
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: 12-1" honeycomb  
(6 coarse + 6 fine)  
1 KHz LPF

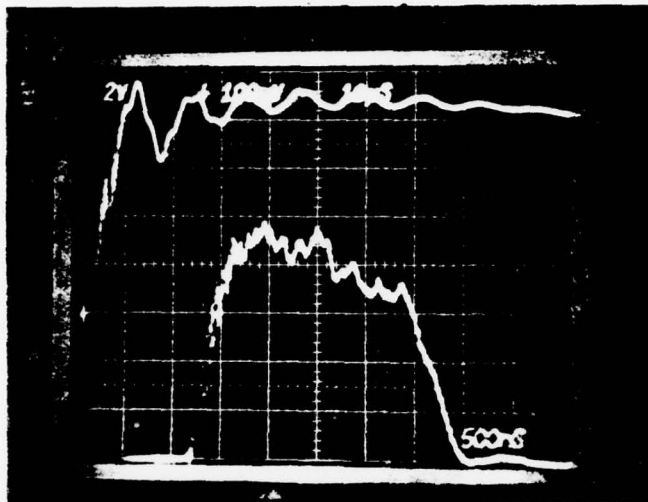
Analyzed Data:

$$E = 70.135$$



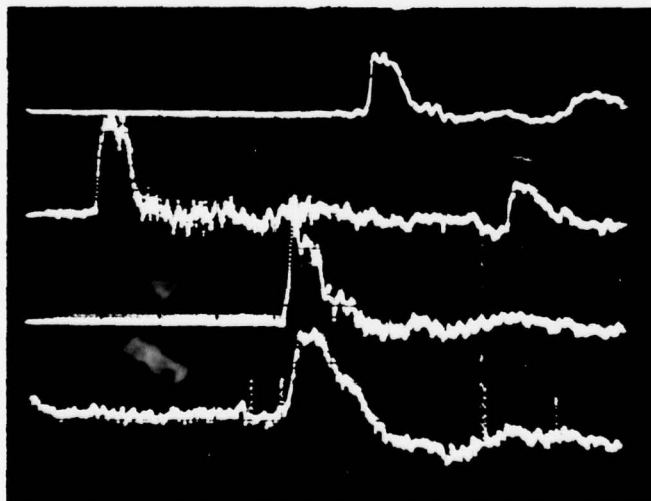
PVC Circulator Experimental Data

Page 221  
No. 5508  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10usec/div  
Inverted? (Yes) No
2. Lower Trace  
Voltage 2V /div  
Time Scale 500nsec/div  
Inverted? Yes (No)  
Attenuation



Voltages

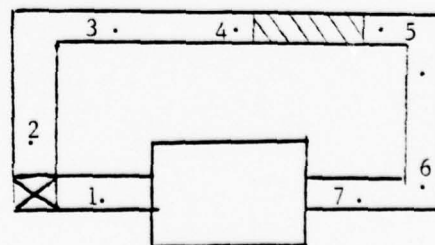
- P<sub>4</sub> Ch. 1 0.02V /div  
P<sub>7</sub> Ch. 2 0.02V /div  
P<sub>5</sub> Ch. 3 0.02V /div  
T<sub>5</sub> Ch. 4 0.05V /div

Time Scale 2msec /div  
Sustainer Voltage 25.8kV  
Flow? On (Off)  
Gas Type N<sub>2</sub>

Notes: 12-1" honeycomb  
(6 coarse + 6 fine)  
1 KHz LPF

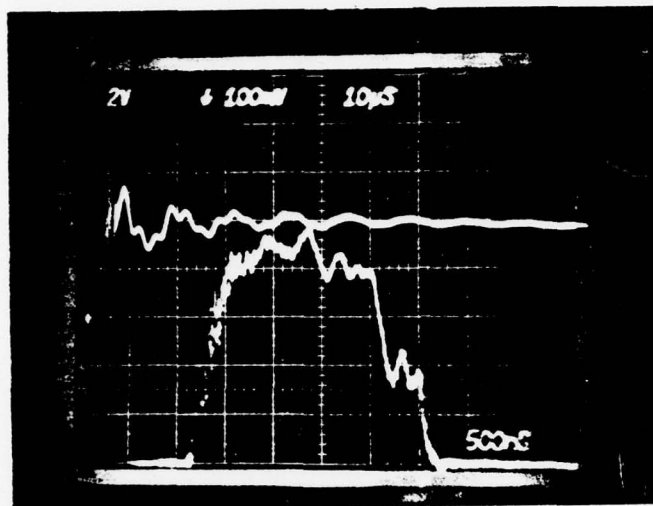
Analyzed Data:

$$E = 65.91$$



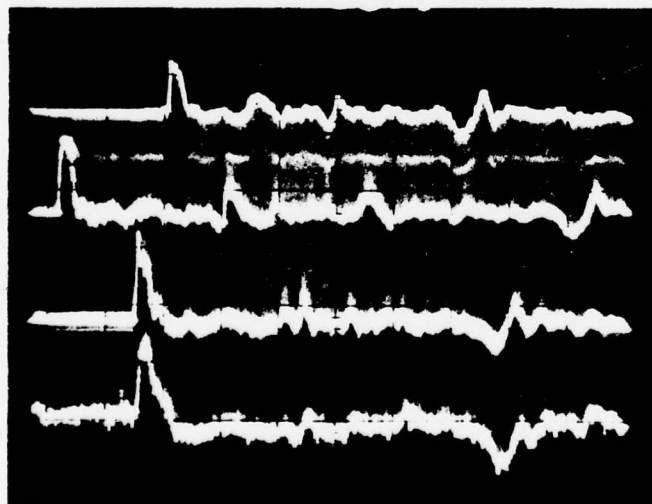
PVC Circulator Experimental Data

Page 222  
No. 5509  
Date 12 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10µsec/div  
Inverted? Yes No
2. Lower Trace  
Voltage 2V /div  
Time Scale 500nsec/div  
Inverted? Yes No  
Attenuation \_\_\_\_\_



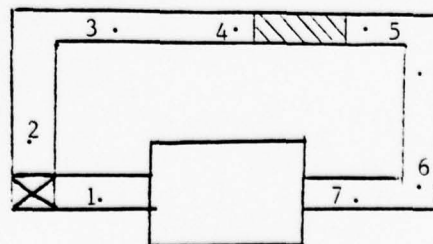
Voltages

- P<sub>4</sub> Ch. 1 0.02V /div  
P<sub>7</sub> Ch. 2 0.02V /div  
P<sub>5</sub> Ch. 3 0.02V /div  
T<sub>5</sub> Ch. 4 0.05V /div

Time Scale 5msec /div  
Sustainer Voltage 25.8kV  
Flow? On Off  
Gas Type N<sub>2</sub>  
Notes: 12-1" honeycomb  
(6 coarse + 6 fine)  
1 KHz LPF

Analyzed Data:

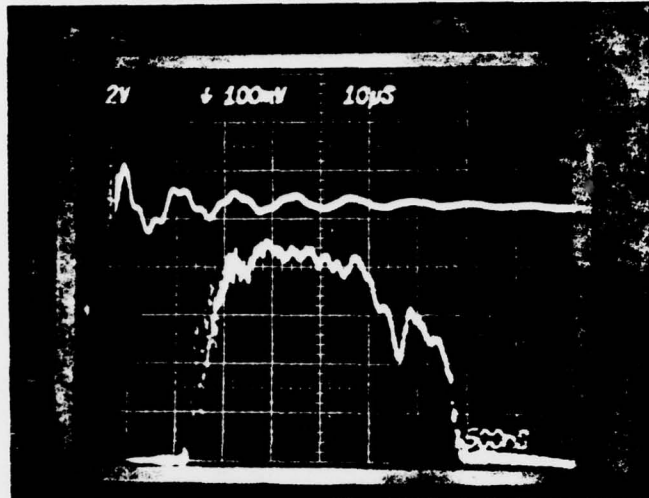
$$E = 54.08$$





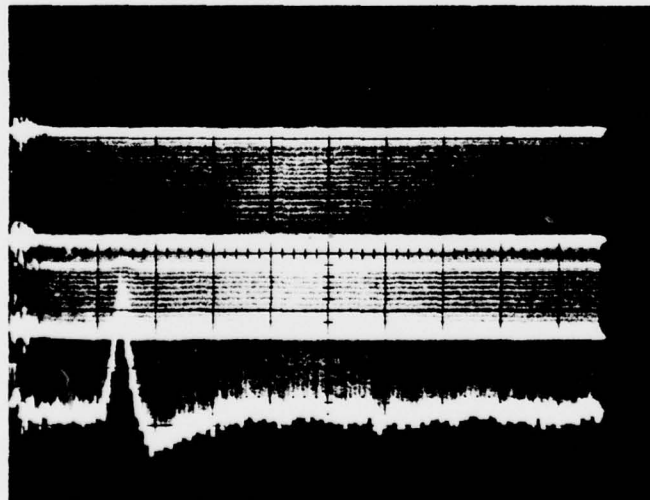
PVC Circulator Experimental Data

Page 223  
 No. 5512  
 Date 12 July 1978



Gun Data

1. Upper Trace  
 Voltage 100mV/div  
 Time Scale 10μsec/div  
 Inverted? ☒ Yes ☐ No
2. Lower Trace  
 Voltage 2V /div  
 Time Scale 500nsec/div  
 Inverted? Yes ☒ No  
 Attenuation \_\_\_\_\_

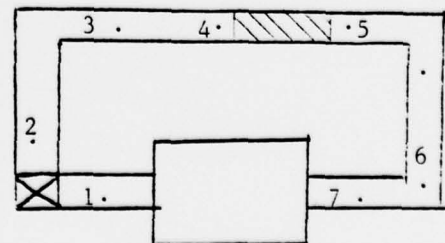


Voltages

P<sub>4</sub> Ch. 1 0.02V /div  
 P<sub>7</sub> Ch. 2 0.02V /div  
 P<sub>5</sub> Ch. 3 0.02V/div  
 T<sub>4</sub> Ch. 4 0.05V /div  
 Time Scale 0.2sec/div  
 Sustainer Voltage 25.8kV  
 Flow? ☒ On ☐ Off  
 Gas Type N<sub>2</sub>  
 Notes: 4-1" honeycomb  
       (2 coarse + 2 fine)  
       1 KHz LPF

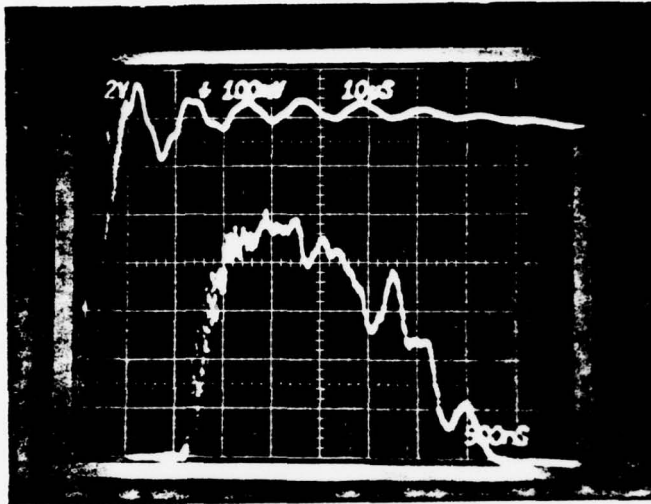
Analyzed Data:

$$E = 64.22$$



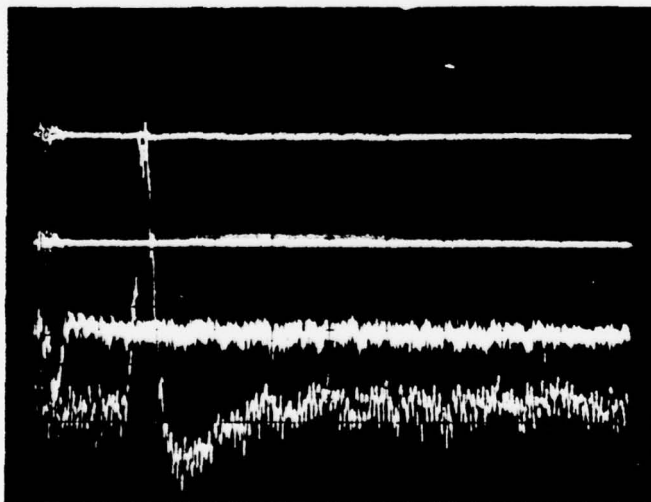
PVC Circulator Experimental Data

Page 224  
No. 5517  
Date 14 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10μs/div  
Inverted? Yes No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes No  
Attenuation \_\_\_\_\_



Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>5</sub> Ch. 2 0.02V/div  
V<sub>1</sub> Ch. 3 0.20V/div  
T<sub>4</sub> Ch. 4 0.02V/div

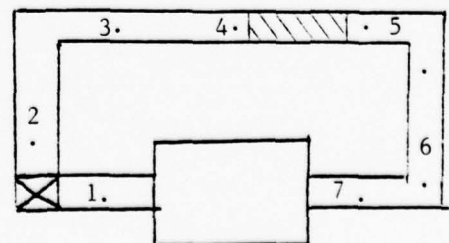
Time Scale 0.2sec/div  
Sustainer Voltage 25.8kV  
Flow? On Off

Gas Type N<sub>2</sub>

Notes: 4-1" honeycomb  
(2 coarse + 2 fine)  
1 KHz LPF

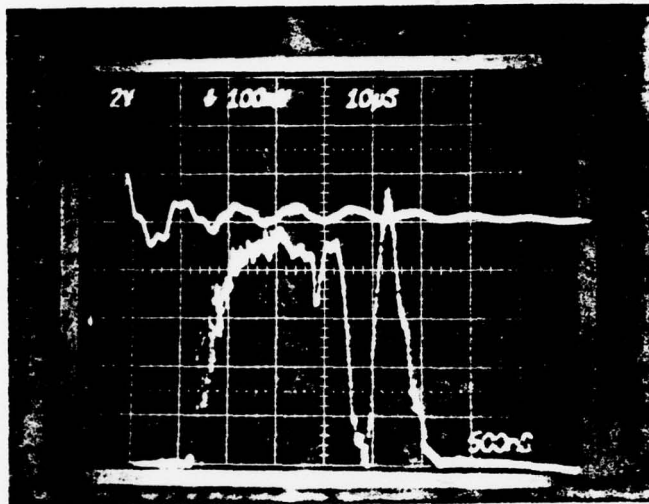
Analyzed Data:

$$E = 65.065$$



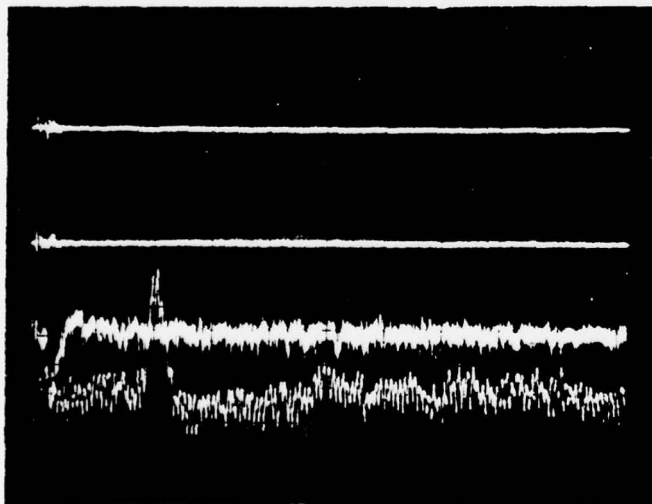
PVC Circulator Experimental Data

Page 225  
 No. 5518  
 Date 14 July 1978



Gun Data

1. Upper Trace  
 Voltage 100mV/div  
 Time Scale 10μsec/div  
 Inverted? Yes No
2. Lower Trace  
 Voltage 2V/div  
 Time Scale 500nsec/div  
 Inverted? Yes No  
 Attenuation \_\_\_\_\_



Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
 P<sub>5</sub> Ch. 2 0.02V/div  
 V<sub>1</sub> Ch. 3 0.20V/div  
 T<sub>5</sub> Ch. 4 0.02V/div

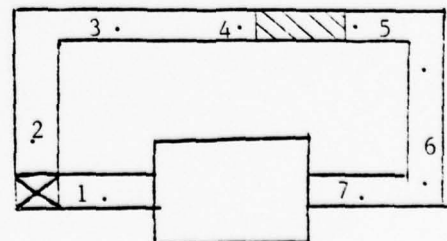
Time Scale 0.2sec/div  
 Sustainer Voltage 25.8kV  
 Flow? On Off

Gas Type N<sub>2</sub>

Notes: 4-1" honeycomb  
 (2 coarse + 2 fine)  
 1 KHz LPF

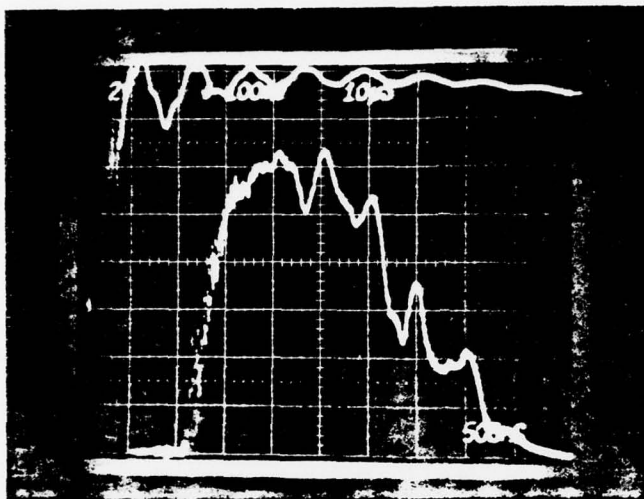
Analyzed Data:

$$E = 55.77$$



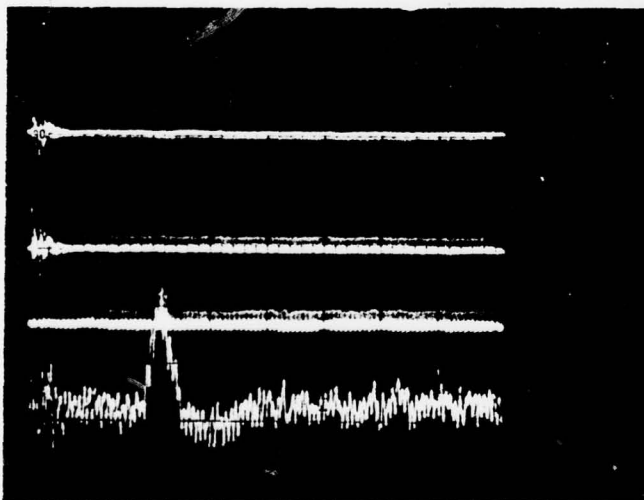
PVC Circulator Experimental Data

Page 226  
No. 5519  
Date 14 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10usec/div  
Inverted? ☒ Yes ☐ No
2. Lower Trace  
Voltage 2v /div  
Time Scale 500nsec/div  
Inverted? Yes ☒ No  
Attenuation \_\_\_\_\_



Voltages

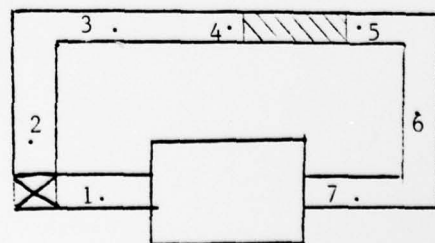
- P<sub>4</sub> Ch. 1 0.02V /div  
P<sub>5</sub> Ch. 2 0.02V /div  
V<sub>4</sub> Ch. 3 0.10V /div  
T<sub>5</sub> Ch. 4 0.02V /div

Time Scale 0.2sec/div  
Sustainer Voltage 25.8kV  
Flow? ☒ On ☐ Off  
Gas Type N<sub>2</sub>

Notes: 4-1" honeycomb  
all small (fine) 1 KHz  
LPF

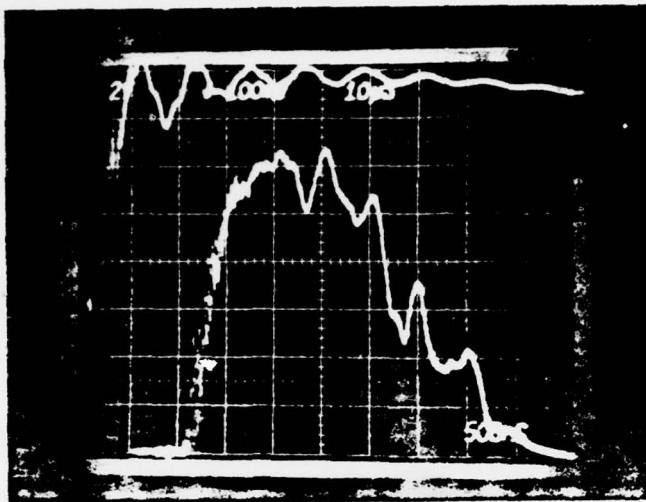
Analyzed Data:

$$E = 87.035$$



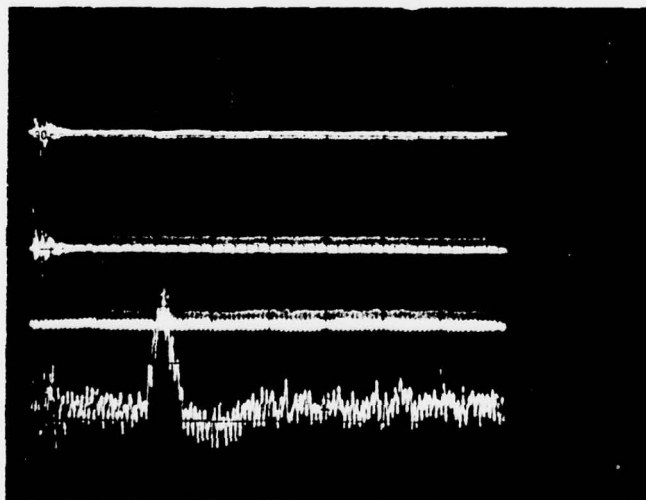
PVC Circulator Experimental Data

Page 226  
No. 5519  
Date 14 July 1978



Gun Data

1. Upper Trace  
Voltage 100mV/div  
Time Scale 10usec/div  
Inverted? Yes No
2. Lower Trace  
Voltage 2V/div  
Time Scale 500nsec/div  
Inverted? Yes No  
Attenuation \_\_\_\_\_



Voltages

- P<sub>4</sub> Ch. 1 0.02V/div  
P<sub>5</sub> Ch. 2 0.02V/div  
V<sub>4</sub> Ch. 3 0.10V/div  
T<sub>5</sub> Ch. 4 0.02V/div

Time Scale 0.2sec/div

Sustainer Voltage 25.8kV

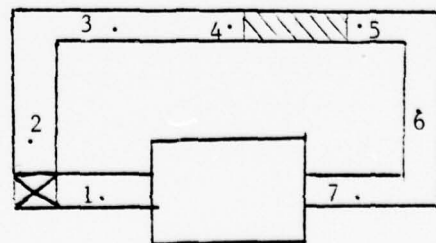
Flow? On Off

Gas Type N<sub>2</sub>

Notes: 4-1" honeycomb  
all small (fine) 1 KHz  
LPF

Analyzed Data:

$$E = 87.035$$



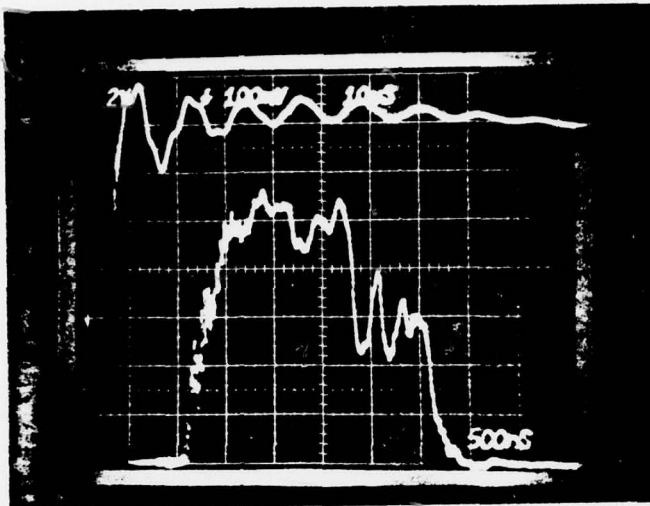


PVC Circulator Experimental Data

Page 227

No. 5521

Date 14 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10nsec/div

Inverted? Yes No

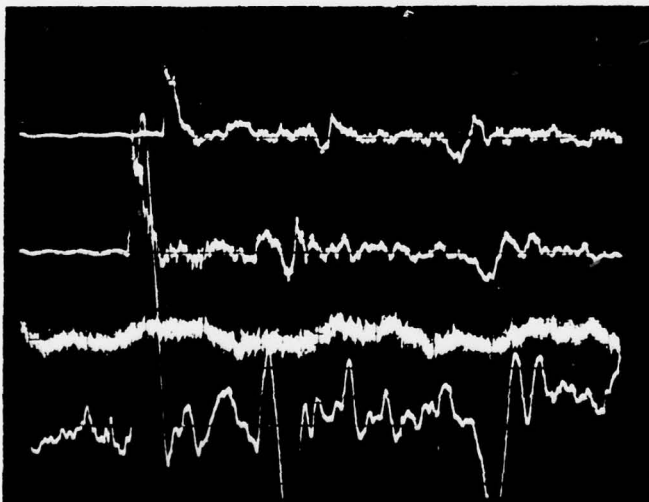
2. Lower Trace

Voltage 2V/div

Time Scale 500nsec/div

Inverted? Yes No

Attenuation           



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>5</sub> Ch. 2 0.02V/div

V<sub>4</sub> Ch. 3 0.02V/div

T<sub>5</sub> Ch. 4 0.02V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

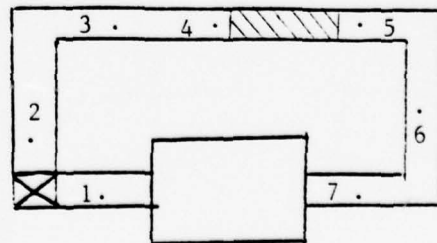
Flow? On Off

Gas Type N<sub>2</sub>

Notes: 4-1" honeycomb  
1 KHz LPF small (fine)

Analyzed Data:

$$E = 67.60$$

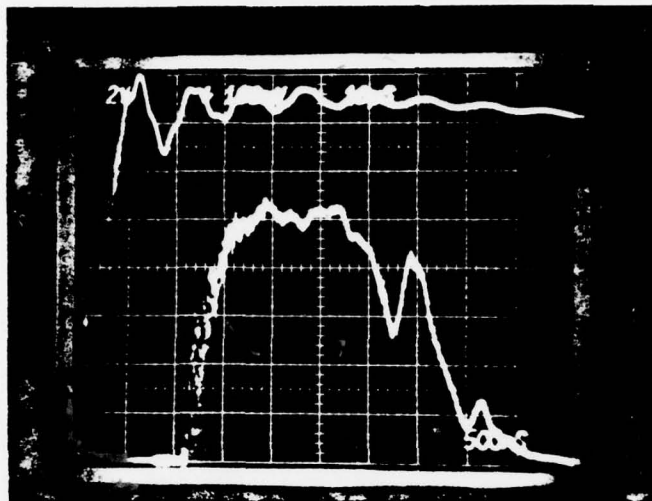


PVC Circulator Experimental Data

Page 228

No. 5522

Date 14 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10usec/div

Inverted? (Yes) No

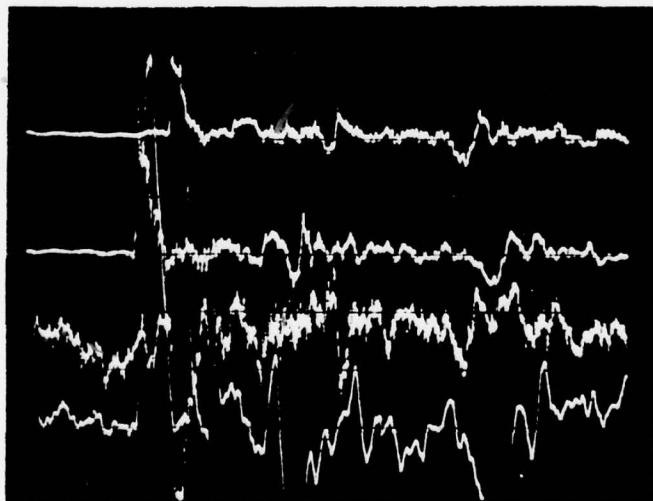
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V/div

P<sub>5</sub> Ch. 2 0.02V/div

V<sub>4</sub> Ch. 3 0.1V/div

T<sub>5</sub> Ch. 4 0.02V/div

Time Scale 5msec/div

Sustainer Voltage 25.8kV

Flow? (On) Off

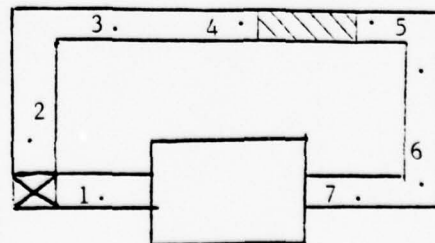
Gas Type N<sub>2</sub>

Notes: 4-1" honeycomb

1 KHz LPF small

Analyzed Data:

$$E = 80.275$$

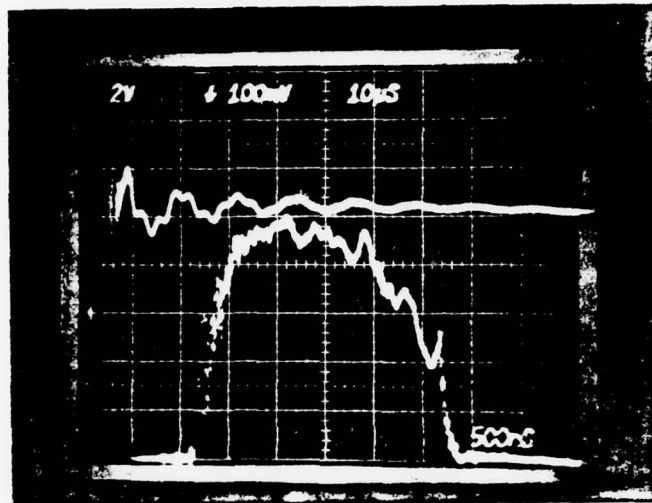


PVC Circulator Experimental Data

Page 229

No. 5523

Date 14 July 1978



Gun Data

1. Upper Trace

Voltage 100mV/div

Time Scale 10nsec/div

Inverted? (Yes) No

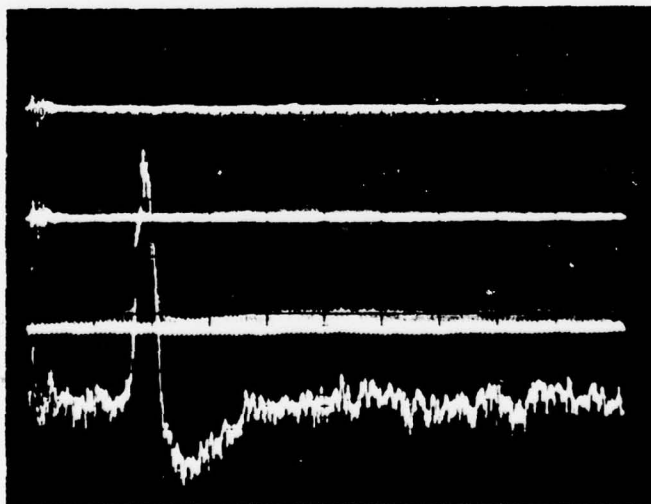
2. Lower Trace

Voltage 2V /div

Time Scale 500nsec/div

Inverted? Yes (No)

Attenuation \_\_\_\_\_



Voltages

P<sub>4</sub> Ch. 1 0.02V /div

P<sub>5</sub> Ch. 2 0.02V /div

V<sub>5</sub> Ch. 3 0.10V /div

T<sub>4</sub> Ch. 4 0.02V /div

Time Scale 0.2sec /div

Sustainer Voltage 25.8kV

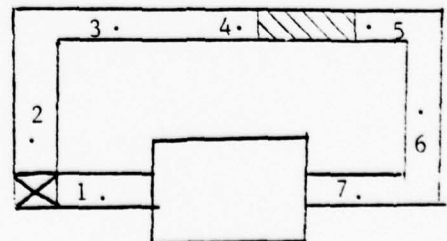
Flow? (On) Off

Gas Type N<sub>2</sub>

Notes: 4-1" honeycomb  
all fine 1 Kz LPF

Analyzed Data:

$$E = 67.60$$



APPENDIX C

```

C  PROGRAM B
C  COMPARE WITH AVCO-EVERETT (P55)
      PARAMETER ISEG=154
      PARAMETER JJ=23
      PARAMETER M=12
      PARAMETER II=ISEG+1
      PARAMETER N=15
      PARAMETER NZ=4
      COMMON /ABC/ XT,G,DT,EI,E0,TI,T0
      COMMON /ASPT/ AZ,SZ,P2,T2
      COMMON /B/ BIC(M)
      COMMON /CONST/ XD,XF
      COMMON /DDD/ G,CP,CV,PF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      COMMON /DLL/ CSL(NZ),CSR(NZ),SL(N),SR(N)
      COMMON /P/ P(M,II,JJ)
      DIMENSION X1(M),X2(M),X3(M)
      DIMENSION BC1(M),BC2(M)
      DIMENSION SW(N)
C  DEFINE CONSTANTS
      SEG=ISEG
      IC=II-1
      MI=II-2
      MJ=JJ-1
C  START OF INDEPENDENT VARIABLES
C  (SEE THE PARAMETERS ALSO)
      CP=0.24
      G=1.4
      XBC11=0.0
      RF=53.34
      XP=2116.3
      XRO=0.00234
      XU=196.3
      XL=1.0
      XXST=0.0
      XXD=0.25
      XF=0.0
      FLAG=-10.0
      XTZ=0.0
      XES=0.0
      RG=5.3683
      DTIME=30.0E-06
      XMF=0.0
      XTI=0.0
      XTO=0.0
      TD=3.5
      SEP=0.5
      XIN=0.1
      XVA=-1.0

```



```

XVB=-3.0
XVC=-5.0
C  END OF INDEPENDENT VARIABLES
F=XF
BC11=XBC11/XL
BC21=SEP*SEG/TD+BC11
X=BC21-BC11
DX=X/SEG
DIS=TD*DX
HX=2.0*DX
CV=CF/G
RR=RF/778.161
R=RF*32.1739
XST=(XXST/G/RR)/(A/XL)
XD=XXD/XL
TZ=A*XTZ/XL
AZ=TZ
ES=XES/G/RR
TI=A*XTI/XL
TO=A*XTO/XL
XT=XP/XPO/R
A=SQRT(G*R*XT)
U=(XU/A)
DT=A*DTIME/XL
CA=(G-1.0)/(2.0*G)
CB=(G+1.0)/(2.0*G)
CC=2.0/(G+1.0)
C  BOUNDARY CONDITIONS (LEFT)
BC1(1)=BC11
BC1(2)=FLAG
BC1(3)=U
BC1(4)=A/A
BC1(5)=ES
BC1(6)=XST
BC1(7)=XD
BC1(8)=XP
BC1(9)=XRO
BC1(10)=XT
BC1(11)=XF
BC1(12)=XNF
C  BOUNDARY CONDITIONS (RIGHT)
BC2(1)=BC21
BC2(2)=FLAG
BC2(3)=U
BC2(4)=A/A
BC2(5)=ES
BC2(6)=XST
BC2(7)=XD
BC2(8)=XP
BC2(9)=XRO
BC2(10)=XT
BC2(11)=XF
BC2(12)=XNF
C  LOAD BOUNDARY CONDITIONS
DO 15 J=1,JJ
DO 14 K=1,M
P(K,1,J)=BC1(K)

```

```

      P(K,II,J)=BIC(K)
14  CONTINUE
15  CONTINUE
C  INITIAL CONDITIONS
      DO 18 I=2,IC
      IM1 = I-1
      P(1,I,1)=P(1,IM1,1)+DX
18  CONTINUE
      BIC(2)=TZ
      BIC(3)=U
      BIC(4)=A/A
      BIC(5)=ES
      BIC(6)=XST
      BIC(7)=XD
      BIC(8)=XP
      BIC(9)=XRO
      BIC(10)=XT
      BIC(11)=XF
      BIC(12)=XNF
C  LOAD INITIAL CONDITIONS
      DO 17 I=2,IC
      DO 16 K=2,M
      P(K,I,1)=BIC(K)
16  CONTINUE
17  CONTINUE
C  CAVITY HEATING (LUMPED ANALYSIS)
      D1=BIC(2)
      S1=BIC(5)
      T1=BIC(10)
      Q=(QG/D1)*(1.0/32.1739)
      DS=Q/T1
      T2=Q/CV+T1
      P2=D1*R*T2
      A2=SQRT(G*R*T2)/A
      S2=(2.0/(G-1.0))*ALOG(A2)-(1.0/G)*ALOG(P2/BIC(3))+S1
      CALL XPPRES(P2,BIC(8),A2,BIC(4),G,PRES)
      XA=1.0+((G+1.0)/(G-1.0))*PRES
      XB=(G+1.0)/(G-1.0)+PRES
      DENS=XA/XB
      TEMP=PRES/DENS
      SPEED=SQRT(TEMP)
C  SHOCK WAVE
      SW(1)=X/2.0
      SW(2)=BIC(2)
      SW(3)=SQRT(CA+CB*PRES)
      SW(4)=CC*(SW(3)-1.0/SW(3))+BIC(3)
      SW(5)=BIC(3)
      SW(6)=PRES*BIC(8)
      SW(7)=BIC(8)
      SW(8)=DENS*BIC(9)
      SW(9)=BIC(9)
      SW(10)=TEMP*BIC(10)
      SW(11)=BIC(10)
      SW(12)=SPEED*BIC(4)
      SW(13)=BIC(4)
      SH=CP*ALOG(TEMP)-RR*ALOG(PRES)
      SW(14)=SH/G/RR+BIC(5)

```

```

      SW(15)=BIC(5)
      SL(1)=SW(1)-DIS
      SR(1)=SW(1)+DIS
      EI=SL(1)
      EO=SR(1)
      DO 32 IK=2,N
      SL(IK)=SW(IK)
      SR(IK)=SW(IK)
32    CONTINUE
      SL(3)=-SW(3)
      SL(4)=BIC(3)-CC*(SW(3)-1.0/SW(3))
C    CONTACT SURFACE
      P22=PRES*BIC(3)
      CSL(1)=SL(1)
      CSL(2)=SL(2)
      CSL(4)=-1.0
      CALL CONT( CSL(4) , P22 , BIC(8) , CSL(3) )
      CSR(1)=SR(1)
      CSR(2)=SR(2)
      CSR(4)=+1.0
      CALL CONT( CSR(4) , P22 , BIC(8) , CSR(3) )
      WRITE(6,299)
299    FORMAT(1H1)
      WRITE(6,300)
300    FORMAT(3X,'LOCATION',3X,'TIME',3X,'MACH',10X,'U2',10X,'U1',10X,
1      'P2',10X,'P1',9X,'R02',9X,'R01')
      WRITE(6,301)
301    FORMAT(14X,'T2',10X,'T1',10X,'A2',10X,'A1',10X,'S2',10X,'S1')
      WRITE(6,109) SL
      WRITE(6,109) SR
109    FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'MAIN'))/)
      WRITE(6,201) CSL
      WRITE(6,201) CSR
201    FORMAT(2X,'INTERFACE',5X,4(2X,E10.4) )
C    SET UP CAVITY CONDITIONS
      DO 33 IK=1,II
      HHX=P(1,IK,1)
      KK=0
      IF(HHX.GE.SL(1).AND.HHX.LE.SR(1)) KK=1
      IF(KK) 33,33,34
34    P(4,IK,1)=A2
      P(5,IK,1)=S2
      P(8,IK,1)=P2
      P(10,IK,1)=T2
33    CONTINUE
C    SOLUTION
      IS=ISEG/2
      IW=IS+1
      DO 13 J=1,MJ
      DO 12 IZ=1,MI
      I=IW-IZ
      IF(IZ.GE.IW) I=IZ
      DO 10 K=1,M
      X1(K)=P(K,I,J)
      IP2 = I+2
      X2(K)=P(K,IP2,J)
10    CONTINUE

```

```

      CALL FIG(M,X1,X2,X3,SL,SR)
      DO 11 K=1,M
      IP1 = I+1
      JP1 = J+1
      P(K,I,J)=X1(K)
      P(K,IP2,J)=X2(K)
      P(K,IP1,JP1) = X3(K)
11  CONTINUE
12  CONTINUE
13  CONTINUE
      P(2,1,JJ)=P(2,2,JJ)
      P(2,II,JJ)=P(2,IC,JJ)
C  END SOLUTION
C  PRINT OUT SPECIAL RESULTS
C  PRINTOUT LOCATIONS
      VA=EI+XVA
      VB=EI+XVB
      VC=EI+XVC
      VV=0.25*BC21
      VH=0.75*BC21
      CALL PLT( VA )
      CALL PLT( VB )
      CALL PLT( VC )
      CALL PLT( VV )
      CALL PLT( EI )
      CALL PLT( SW(1))
      CALL PLT( EC )
      CALL PLT( VH )
      PI=EI-2.0*DIS
      PE=EC+2.0*DIS
      IF(PI.LT.BC11) PI=BC11
      IF(PE.GT.BC21) PE=BC21
      DA=PI-XIN
3   CONTINUE
      DA=DA+XIN
      CALL PLT( DA )
      IF(DA.LE.PE) GO TO 3
C  PRINTOUT
      WRITE(6,1)
1   FORMAT(1H1,6X,'ARRAY P(K,I,J)')
      DO 20 J=1,JJ
      DO 19 I=1,II
      WRITE(6,2) I,J,(P(K,I,J),K=1,M)
2   FORMAT(2(2X,I3),2(2X,E9.4),2X,E10.4,8(2X,E8.3),2X,F4.1)
19  CONTINUE
20  CONTINUE
      END

```

```

SUBROUTINE RADIUS(N,X,Y,Z,LD)
DIMENSION X(N),Y(N),Z(N)
R=0.01
EX=X(1)
TX=X(2)
EY=Y(1)
TY=Y(2)
EZ=Z(1)
TZ=Z(2)
DA=SGRT( (EZ-EX)**2+ (TZ-TX)**2 )
DB=SGRT( (EZ-EY)**2 + (TZ-TY)**2 )
IF( DA .LE. R ) LD=1
IF( DB .LE. R ) LD=1
IF(LD)2,2,1
1 WRITE(6,3) R,EX,TX,EY,TY,EZ,TZ
3 FORMAT(2X,'RADIUS',2X,7(F12.5,2X) )
2 CONTINUE
RETURN
END

```

```

SUBROUTINE SSS(NN,AA1,AA2,AA3)
PARAMETER M=12
DIMENSION AA1(NN),AA2(NN),AA3(NN)
DIMENSION AA4(M),HH3(M)
AA3(3)=(AA1(3)+AA2(3))/2.0
AA3(4)=(AA1(4)+AA2(4))/2.0
AA4(3)=AA3(3)
LL=0
LD=0
101 CONTINUE
LL=LL+1
LMAX=5
LN=LL-LMAX
IF(LN) 103,103,105
103 CONTINUE
CALL GEO(NN,AA1,AA2,AA3,AA4)
CALL SOL(NN,AA1,AA2,AA3,AA4,HH3)
C TEST ROUTINE
CALL RADIUS(NN,AA1,AA2,AA3,LD)
IF( LD .GT. 0 ) GO TO 104
TX=0.001
II=0
IF(AA3(3).EQ.0.0) AA3(3)=1.0E-6
IF(AA3(4).EQ.0.0) AA3(4)=1.0E-6
RV=(AA3(3)-HH3(3))/AA3(3)

```



```

      RA=(AA3(4)-HH3(4))/AA3(4)
      IF(ABS(PV).GT.TX) II=II+1
      IF(ABS(RA).GT.TX) II=II+1
      IF(II) 102,102,101
102  CONTINUE
      GO TO 104
105  WRITE(6,105) TX,RV,RA,AA3(1),AA3(2),LMAX
106  FORCAT(1X,5(2X,E10.4),3X,'LMAX=',15,2X,'SSS')
      WRITE(6,1)(AA1(IM),IM=1,M)
      WRITE(6,2)(AA2(IM),IM=1,M)
1    FORMAT(1X,12(2X,E8.3),2X,'AA1')
2    FORMAT(1X,12(2X,E8.3),2X,'AA2')
104  CONTINUE
      CALL PPP(NN,AA1,AA3)
      AA3(12)=LL
      RETURN
      END

```

```

SUBROUTINE GEO(NN,AA1,AA2,AA3,AA4)
COMMON /CONST/ XD,XF
DIMENSION AA1(NN),AA2(NN),AA3(NN),AA4(NN)
R13=(AA1(3)+AA1(4)+AA2(3)+AA2(4))/2.0
S13=1.0/R13
R23=(AA2(3)-AA2(4)+AA3(3)-AA3(4))/2.0
S23=1.0/R23
B13=AA1(2)-S13*AA1(1)
B23=AA2(2)-S23*AA2(1)
AA3(1)=(B23-B13)/(S13-S23)
AA3(2)=S13*AA3(1)+B13
S12=(AA1(2)-AA2(2))/(AA1(1)-AA2(1))
B12=AA1(2)-S12*AA1(1)
R34=(AA3(3)+AA4(3))/2.0
S34=1.0/R34
B34=AA3(2)-S34*AA3(1)
AA4(1)=(B12-B34)/(S34-S12)
AA4(2)=S34*AA4(1)+B34
PF=(AA2(1)-AA4(1))/(AA2(1)-AA1(1))
AA4(5)=(1.0-PF)*AA2(5)+PF*AA1(5)
CALL HEAT(AA3(1),AA3(2),AA3(3),AA3(4),AA3(5),AA3(6))
CALL HEAT(AA4(1),AA4(2),AA4(3),AA4(4),AA4(5),AA4(6))
AA3(7)=XD
AA3(11)=XF
AA4(7)=XD
RETURN
END

```

```

SUBROUTINE HEAT(E,T,UU,AA,S,H)
COMMON /ABC/ XT,Q,DT,EI,EO,TI,TO
COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
TE=(AA*AA/1.0/1.0)*XT
I=0
H=0.0
XH=Q/(TE*DT*G*RR)
IF(E.GT.EI.AND.E.LT.EO) I=I+1
IF(T.GT.TI.AND.T.LT.TO) I=I+1
IF(I.EQ.2) H=XH
RETURN
END

```

```

SUBROUTINE SOL(NN,AA1,AA2,AA3,AA4,HH3)
COMMON /DDD/ G,CP,CV,PF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
DIMENSION AA1(NN),AA2(NN),AA3(NN),AA4(NN),HH3(NN)
DO 10 I=1,NN
HH3(I)=AA3(I)
10 CONTINUE
FU=((AA2(1)-AA4(1))/(AA2(1)-AA1(1)))*(AA1(3)-AA2(3))+AA2(3)
SU=((AA2(2)-AA4(2))/(AA2(2)-AA1(2)))*(AA1(3)-AA2(3))+AA2(3)
AA4(3)=0.5*(FU+SU)
S4=AA4(5)
DS43=(AA4(6)+HH3(6))/2.0
P1=(2.0/(G-1.0))*AA1(4)+AA1(3)
Q2=(2.0/(G-1.0))*AA2(4)-AA2(3)
A13=(AA1(4)+HH3(4))/2.0
A23=(AA2(4)+HH3(4))/2.0
U13=(AA1(3)+HH3(3))/2.0
U23=(AA2(3)+HH3(3))/2.0
DS13=(AA1(6)+HH3(6))/2.0
DS23=(AA2(6)+HH3(6))/2.0
F13=(AA1(11)+HH3(11))/2.0
F23=(AA2(11)+HH3(11))/2.0
D13=(AA1(7)+HH3(7))/2.0

D23=(AA2(7)+HH3(7))/2.0
DD13=(AA1(7)**2+HH3(7)**2)/2.0
DD23=(AA2(7)**2+HH3(7)**2)/2.0
DA31=(AA3(7)**2-AA1(7)**2)/DD13/(AA3(1)-AA1(1))
DA32=(AA3(7)**2-AA2(7)**2)/DD23/(AA3(1)-AA2(1))
T1=AA1(2)
T2=AA2(2)
T3=HH3(2)
T4=AA4(2)
S1=AA1(5)
S2=AA2(5)
C START GOVERNING EQUATIONS
S3=S4+DS43*(T3-T4)
P3=P1+A13*(S3-S1)
1 + ( (G-1.0)*A13*DS13
1 - A13*U13*DA31
1 - F13*U13*ABS(U13)/2.0/D13 )*(T3-T1)
G3=Q2+A23*(S3-S2)
1 + ( (G-1.0)*A23*DS23
1 - A23*U23*DA32
1 - F23*U23*ABS(U23)/2.0/D23 )*(T3-T2)
C END GOVERNING EQUATIONS
AA3(3)=(P3-G3)/2.0
AA3(4)=(G-1.0)*(P3+G3)/4.0
AA3(5)=S3
RETURN
END

SUBROUTINE PPP(NN,AA1,AA3)
COMMON /DDD/ G,CP,CV,PF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
DIMENSION AA1(NN),AA3(NN)
C1=(2.0/(G-1.0))*ALOG(AA3(4)/AA1(4))
C2=G*(AA3(5)-AA1(5))
AA3(9)=AA1(9)*EXP(C1-C2)
AA3(10)=A*A*AA3(4)*AA3(4)/G/R
AA3(8)=AA3(9)*R*AA3(10)
RETURN
END

```

```

SUBROUTINE FIG(NX,AA1,AA2,AA3,SWL,SWR)
PARAMETER M=12
PARAMETER N=15
DIMENSION AA1(NX),AA2(NX),AA3(NX)
DIMENSION AA4(N)
DIMENSION SWL(N),SWR(N)
IF(AA1(1).LT.(0.0)) AA1(2)=AA2(2)
IF(AA2(2).LT.(0.0)) AA2(2)=AA1(2)
AA3(3)=(AA1(3)+AA2(3))/2.0
AA3(4)=(AA1(4)+AA2(4))/2.0
AA4(3)=AA3(3)
NM=0
CALL CHKR(NX,AA1,AA2,AA3,AA4,SWR,NM)
IF(NM) 109,109,107
109 CONTINUE
MM=0
CALL CHYL(NX,AA1,AA2,AA3,AA4,SWL,MM)
IF(MM) 110,110,107
110 CONTINUE
CALL SUB(NX,AA1,AA2,AA3)
107 CONTINUE
RETURN
END

```

```

SUBROUTINE SUB(N,A,B,C)
PARAMETER NZ=4, NA=15
COMMON /DLL/ CSL(NZ),CSR(NZ),SL(NA),SP(NA)
DIMENSION A(N),B(N),C(N)
NM=0
CALL CCS(N,A,B,C,CSL,NM)
IF(NM) 109,109,107
109 CONTINUE
MM=0
CALL CCS(N,A,B,C,CSR,MM)
IF(MM) 110,110,107
110 CONTINUE
CALL SSS(N,A,B,C)
107 CONTINUE
RETURN
END

```

```

SUBROUTINE XPRES(P4,P1,A4,A1,B,PRES)
XX=0.001
PRES=1.0-XX
EX=-2.0*G/(G-1.0)
PRES=PRES+XX
XA=(G-1.0)*(A1/A4)*(PRES-1.0)
XB=SQRT(2.0*G)
XC=SQRT(2.0*G+(G+1.0)*(PRES-1.0))
PP=P1*PRES*((1.0-XA/XB/XC)**EX)
TF=0.005
Y=ABS((P4-PP)/P4)
IF(Y.GT.TF) GO TO 1
RETURN
END

```

```

SUBROUTINE RAN(NN,BB1,BB2,PR,XX)
COMMON /DDD/ G,CP,CV,PF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
DIMENSION BB1(NN),BB2(NN)
XA=1.0+((G+1.0)/(G-1.0))*PR
XB=(G+1.0)/(G-1.0)+PR
BB2(1)=BB1(1)
BB2(2)=BB1(2)
BB2(6)=BB1(6)
BB2(7)=BB1(7)
BB2(8)=PR*BB1(8)
BB2(9)=BB1(9)*(XA/XB)
BB2(10)=BB1(10)*PR*(XB/XA)
BB2(11)=BB1(11)
V1=SQRT(CA+CB*PR)
V2=V1*(BB1(9)/BB2(9))
BB2(3)=U+XX*(V1-V2)
BB2(4)=SQRT(G*R*BB2(10))/A
BH=CP*ALOG(BB2(10)/BB1(10))-RR*ALOG(PR)
BB2(5)=BH/G/RR+BB1(5)
RETURN
END

```

```

SUBROUTINE SZ(NN,XN,Z)
PARAMETER NZ=4, N=15
COMMON /CONST/ XD,XF
COMMON /DLL/ CSL(NZ),CSR(NZ),SL(N),SR(N)
DIMENSION Z(NN)
IF(XN.LT. 0.0 ) Z(3)=SL(4)
IF(XN.GT. 0.0 ) Z(3)=SR(4)
Z(4)=SL(12)
Z(5)=SL(14)
Z(6)=0.0
Z(7)=XD
Z(8)=SL(6)
Z(9)=SL(8)
Z(10)=SL(10)
Z(11)=XF
Z(12)=-7.0
RETURN
END

```

```

SUBROUTINE CHKL(NN,X,Y,Z,AB,SW,ID)
PARAMETER M=12, N=15
COMMON /B/ BIC(M)
COMMON /CONST/ XD,XF
COMMON /DDD/ G,CP,CV,PF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
DIMENSION X(NN),Y(NN),Z(NN),AB(NN)
DIMENSION SW(N),XP(M),XQ(M),YP(M)
50  FORMAT(2X,'SW LEFT',5X,'E=',F12.5,5X,'TO=',F12.5)
ID=0
IZ=0
IL=IZ
IR=IZ

```

```

      XN=-1.0
      PR=SW(6)/BIC(8)
      RSL=X(3)+X(4)
      SL=1.0/RSL
      BL=X(2)-SL*X(1)
      RSR=Y(3)-Y(4)
      SR=1.0/RSR
      BR=Y(2)-SR*Y(1)
      PE=(BL-BR)/(SR-SL)
      PT=SL*PE+BL
      RSS=U+SW(3)
      SS=1.0/RSS
      BS=SW(2)-SS*SW(1)
      YP(1)=(BR-BS)/(SS-SR)
      YP(2)=SS*YP(1)+BS
      XP(1)=(BL-BS)/(SS-SL)
      XP(2)=SS*XP(1)+BS
      IF( YP(1) .GE. PE .AND. YP(1) .LE. Y(1) ) IR=10
      IF( XP(1) .GE. X(1) .AND. XP(1) .LT. PE ) IL=100
      IF( IL .EQ. IZ .AND. IR .EQ. IZ ) GO TO 100
      IF( IL .EQ. IZ .AND. IR .GT. IZ ) GO TO 70
      IF( IL .GT. IZ .AND. IR .GT. IZ ) GO TO 80
      IF( IL .GT. IZ .AND. IR .EQ. IZ ) GO TO 90
70    CONTINUE
      Z(1)=PE
      Z(2)=PT
      DO 71 I=3,4
      Z(I)=BIC(I)
71    CONTINUE
201   FORMAT(2X,'CHKL',4(2X,E10.4),3(2X,I6) )
5     FORMAT(2(2X,E9.4),2X,E10.4,3(2X,E8.3),2X,F4.1)
      WRITE(6,201) YP(1),YP(2),XP(1),XP(2),IZ,IL,IR
      WRITE(6,5) Z
      GO TO 100
80    CONTINUE
      Z(1)=PE
      Z(2)=PT
      CALL SZ(NN,XN,Z)
      WRITE(6,201) YP(1),YP(2),XP(1),XP(2),IZ,IL,IR
      WRITE(6,5) Z
      GO TO 100
90    DO 91 I=3,4
      XP(I)=X(I)
91    CONTINUE
      CALL HEAT(XP(1),XP(2),XP(3),XP(4),XP(5),XP(6) )
      XP(7)=XD
      XP(11)=XF
      XP(12)=BIC(12)
      CALL RAN(NN,XP,XG,PR,XN)
      WRITE(6,50) XG(1),XG(2)
      CALL SUB(NN,XG,Y,Z)
      ID=90
      WRITE(6,201) YP(1),YP(2),XP(1),XP(2),IZ,IL,IR
      WRITE(6,5) Z
      GO TO 100
100   CONTINUE
      RETURN

      END

```



```

SUBROUTINE CHKR(NN,X,Y,Z,AB,SW,ID)
PARAMETER M=12, N=15
COMMON /B/ BIC(M)
COMMON /CONST/ XD,XF
COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
DIMENSION X(NN),Y(NN),Z(NN),AB(NN)
DIMENSION SW(N),XP(M),YP(M),YG(M)
50  FORMAT(2X,'SW RIG-T',5X,'E=',F12.5,5X,'TO=',F12.5)
ID=0
IZ=0
IL=IZ
IR=IZ
XN=+1.0
PR=SW(6)/BIC(6)

RSL=X(3)+X(4)
SL=1.0/RSL
BL=X(2)-SL*X(1)
RSR=Y(3)-Y(4)
SR=1.0/PSR
BR=Y(2)-SR*Y(1)
PE=(BL-BR)/(SR-SL)
PT=SL*PE+BL
RSS=U+SW(3)
SS=1.0/RSS
BS=SW(2)-SS*SW(1)
YP(1)=(BR-BS)/(SS-SR)
YP(2)=SS*YP(1)+BS
XP(1)=(BL-BS)/(SS-SL)
XP(2)=SS*XP(1)+BS
IF( XP(1) .GE. X(1) .AND. XP(1) .LE. PE ) IL=10
IF( YP(1) .GT. PE .AND. YP(1) .LE. Y(1) ) IR=100
IF( IL .EQ. IZ .AND. IR .EQ. IZ ) GO TO 100
IF( IL .GT. IZ .AND. IR .EQ. IZ ) GO TO 70
IF( IL .GT. IZ .AND. IR .GT. IZ ) GO TO 80
IF( IL .EQ. IZ .AND. IR .GT. IZ ) GO TO 90
70  CONTINUE
Z(1)=PE
Z(2)=PT
DO 71 I=3,M
Z(I)=BIC(I)
71  CONTINUE
GO TO 100
90  CONTINUE
Z(1)=PE
Z(2)=PT
CALL SZ(NN,XN,Z)
GO TO 100
90  DO 91 I=3,M
YP(I)=Y(I)
91  CONTINUE
CALL HEAT(YP(1),YP(2),YP(3),YP(4),YP(5),YP(6) )
YP(7)=XD
YP(11)=XF
YP(12)=BIC(12)
CALL RAN(NN,YP,YG,PR,XN)
WRITE(6,50) YG(1),YG(2)
CALL SUB(NN,X,YG,Z)
ID=90
GO TO 100
100 CONTINUE
RETURN
END

```

```

SUBROUTINE CCS(M,X,Y,Z,FACE,IN)
PARAMETER NZ=4
PARAMETER NX=12
COMMON /CONST/ XD,XF
COMMON /DDD/ G,CP,CV,PF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
DIMENSION X(M),Y(M),Z(M)
DIMENSION FACE(NZ),AB(NX),YY(NX)
DIMENSION XX(NX)
IN=0
XHX=4.0
XXL=X(1)-FACE(1)
IF(XXL.GT.XHX) GO TO 200
YYL=FACE(1)-Y(1)

IF(YYL.GT.XHX) GO TO 200
IF(X(1).EQ.FACE(1).AND.X(2).EQ.FACE(2)) GO TO 200
IF(Y(1).EQ.FACE(1).AND.Y(2).EQ.FACE(2)) GO TO 200
RCS=FACE(3)
SCS=1.0/RCS
BCS=FACE(3)-SCS*FACE(1)
Z(3)=(X(3)+Y(3))/2.0
Z(4)=(X(4)+Y(4))/2.0
AB(3)=Z(3)
CALL GEO(M,X,Y,Z,AB)
PL=(2.0/(G-1.0))*X(4)+X(3)
QR=(2.0/(G-1.0))*Y(4)-Y(3)
SL=X(5)
SR=Y(5)
CAL=0.25*(G-1.0)*(SL-SR)
QL=(PL+QR)*TANH(CAL)+QR
PR=(QR-QL)+PL
VL=(PL-QL)/2.0
VR=(PR-QL)/2.0
CL=0.25*(G-1.0)*(PL+QL)
CP=0.25*(G-1.0)*(PR+QR)
V=0.5*(VL+VR)
C RIGHT LEG ONLY
S23=(Z(2)-Y(2))/(Z(1)-Y(1))
B23=Y(2)-S23*Y(1)
E=(BCS-B23)/(S23-SCS)
T=S23*E+B23
IF(E.GE.Z(1).AND.E.LE.Y(1)) GO TO 101
GO TO 102
101 CONTINUE
98 FORMAT(2X,6(2X,F12.4),5X,'CCS 1')
99 FORMAT(2X,6(2X,F12.4),5X,'CCS 2')
WRITE(6,98) X(3),X(4),Y(3),Y(4),SL,SR
WRITE(6,99) QL,PR,VL,VR,V,CAL
IN=101
YY(1)=E
YY(2)=T
YY(3)=V
YY(4)=CL
YY(5)=X(5)
CALL HEAT(YY(1),YY(2),YY(3),YY(4),YY(5),YY(6))
YY(7)=XD
YY(11)=YF
CALL CCS(M,X,YY,Z)
FACE(1)=E
FACE(2)=T
FACE(3)=V

```

```

      WRITE(6,1) FACE
1     FORMAT(2X,'INTERFACE',5X,4(2X,E10.4) )
      GO TO 200
102    CONTINUE
C     LEFT LEG ONLY
      S12=(Z(2)-X(2))/(Z(1)-X(1))
      S12=X(2)-S12*X(1)
      E=(PCS-B12)/(S12-SCS)
      T=S12*E+B12
      IF(E.GE.X(1).AND.E.LE.Z(1)) GO TO 103

      GO TO 200
103    CONTINUE
      WRITE(6,98) X(3),X(4),Y(3),Y(4),SL,SR
      WRITE(6,99) GL,PR,VL,VR,V,CAL
      IN=103
      XX(1)=E
      XX(2)=T
      XX(3)=V
      XX(4)=CR
      XX(5)=Y(5)
      CALL HEAT(XX(1),XX(2),XX(3),XX(4),XX(5),XX(6))
      XX(7)=XD
      XX(8)=Y(9)
      XX(11)=XF
      CALL SSS(M,XX,Y,Z)
      FACE(1)=E
      FACE(2)=T
      FACE(3)=V
200    WRITE(6,1) FACE
      CONTINUE
      RETURN
      END

```

```

SUBROUTINE COM(NN,C1,C2,C3)
DIMENSION C1(NN),C2(NN),C3(NN)
P=(C2(1)-C1(1))/(C3(1)-C1(1))
DO 10 I=3,NN
C2(I)=P*C3(I)+(1.0-P)*C1(I)
10 CONTINUE
RETURN
END

```

```

SUBROUTINE CONT(XN,P2,P1,YG)
COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
PRES=P2/P1
IF(PRES.LT.1.0) PRES=1.0/PRES
YA=PRES-1.0
YB=2.0/C
YC=(G+1.0)*PRES
YD=G-1.0
YF=YA*SGRT(YB/(YC+YD))
IF(XN.LT.0.0) YG=U-YF
IF(XN.GT.0.0) YG=U+YF
RETURN
END

```

APPENDIX D

```

      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION AMT(13,13), NN(13), SVR(13), TDIF(13), BMT(13)
      COMMON /VAR/ T01G, T02G, T06G, T07G, T1, T2, T3, T4, T6, T8,
1  T10, T14, T16, T18, T20, TA2, T08G, T7,
2  T03G, T04G, T05G, T09G, T010G, T011G, T5, T9, T11,
3  T12, T13, T15, T17, T19, T13, T2G, T3G, T4G, T5G, T6G, T7G,
4  T8G, T9G, T10G, T11G, TA1, EFFL, P01G, P02G, P03G, P04G, P05G,
5  P06G, P07G, P08G, P09G, P010G, P011G, P1G, P2G, P3G, P4G, P5G,
6  P6G, P7G, P8G, P9G, P10G, P11G, P(20), AC(20), VC(20), FM1,
7  FM2, FM3, FM4, FM5, FM6, FM7, FM8, FM9, FM10, FM11, A(11),
8  GAM1G, GAM2G, GAM3G, GAM4G, GAM5G, GAM6G, GAM7G, GAM8G, GAM9G,
9  GAM10G, GAM11G, TGM1, TGM2, TGM3, TMA, GIMU, GIIMU, GZMU, AMU,
1  PRG1,
2  PRG2, PRG3, PRA, CPG1, CPG2, CPG3, CPA, TMI, TM2, TM3, TM4, TM,
3  ZIMU, ZIIMU, Z3MU, ZMU,
4  PRI, PR2, PR3, PR, CPI, CPI2, CPI3, CP, GCI, GCI2, GCI3,
5  1GA, GI, GI2, GI3, G, REG1,
6  REG2, REG3, REA, RE1, RE2, RE3, RE, GFI, GFI2, GFI3,
7  COMMON/VARB/ AF, FI, FII, F, GJI,
8  GJ2, GJ3, AJ, ZJI, ZJ2, ZJ3, ZJ, HGI, HGI2, HGI3, HA,
9  HI, H2, H3, H, CCI, CCI2, CCI3,
1  CA, C1, C2, C3, C, UI, U2, U3, U, AGI, AG2, AG3, AA,
2  TUN1, TUN2, TUN3, TUN,
3  TOW1, TOW2, TOW3, TOW, EPS1, EPS2, EPS3, EPSA, ESS1, ESS2,
4  ESS3, ESS, WG,
5  Q6G, QCORR, BPR, ALT, PAT, PA2, RH, FN(4), EFFLP, VI, VIM,
6  PIGA, H1M, CL1M, WT1M, DCM, BLPR, BLPRM, CPP, CPPM, PF, PFM,
7  RO1, PLKW, WI, W2, W3, W, WM, WV1, WV2, WE, WS, WA, GP, GCM,
8  QM, QV1, QV2, QE, QS, CF23, CF34, CF45, CF72, CF89, CF910
9  COMMON /VARC/CF111, ATAP, H1, CL1, WT1, ACN(20), DC, DL(4),
1  DK(4), DW(4), DDHG(4), DALG(4), DAFOA(4), DSIG(4), DDEL(4),
2  DA(4), DK(3), DSL(4), DSI(4), DALF(4), DDH(4), CONV(16), DELM,
3  ROLIM, PLIM, FG, TITLE(28), DP, DPI, DPI2, DPI3, PPR, PPRM,
4  TA1F, RHP, TIGM, DKH(4), ETIG, ET02G, ET06G, ET07G, ET1,
5  ET2, ET3, ET4, ET6, ET8, ET10, ET14, ET16, ET18, ET20, ETA2,
6  ET08G, ET7,
7  EBPR, CWA, DNP(3), GDI, GDI2, GDI3,
8  GDA, EVIM, BRPM, VLM, ROA1,
9  ROA2, DAFAL(4), DSLL(4), AB(4)
1  COMMON/VARD/GO, GCG, CP2, CP6, W3, CP3, CP1, FIII, TUN3
2  COMMON /IVAR/ NTAM, NDSGN, NCS, KI, KO, NLM, NP(4), NFULL,
3  NBS, NBPS, JCPRO
4  EQUIVALENCE (SVR( 1),T01G)
5  WRITE(6,10021)T01G, T02G, T06G, T07G, T1, T2, T3, T4, T6, T8,
6  T10, T14, T16, T18, T20, TA2
10021 FORMAT(1H0,3X,'T01G=',E15.7,5X,'T02G=',E15.7,5X,'T06G=',E15.7,
15X,'T07G=',E15.7,5X,'T1=',E15.7,5X,'T2=',E15.7,5X,'T3=',E15.7,
25X,'T4=',E15.7,5X,'T6=',E15.7,5X,5X,'T8=',E15.7,5X,'T10=',
3E15.7,5X,'T14=',E15.7,5X,'T16=',E15.7,5X,5X,'T18=',E15.7,5X,
4'T20=',E15.7,5X,'TA2=',E15.7)

```

2 CALL INPUT



```

SUBROUTINE PLT( XY )
PARAMETER ISEG=154
PARAMETER II=ISEG+1
PARAMETER JJ=23
PARAMETER M=12
COMMON /P/ P(M,II,JJ)
DIMENSION A(M),B(M),C(M)
ZZZ=1.0E-06
WRITE(6,454)
459 FORMAT(1H1)
IYO=II-1
DO 450 J=1,JJ
B(1)=XX
IL=0
IX=0
DO 451 I=1,IYO
IP1=I+1
IF(XY.GT.P(1,I,J).AND.XX.LT.P(1,IP1,J)) IL=I
IF(ABS(XY-P(1,I,J)).LE.ZZZ) IX=I
451 CONTINUE
IF(IL) 452,452,453
453 ILP=IL+1
B(2)=0.5*(P(2,IL,J)+P(2,ILP,J))
DO 456 LX=1,M

A(LX)=P(LX,IL,J)
C(LX)=P(LX,ILP,J)
456 CONTINUE
CALL CON(M,A,B,C)
452 IF(IX) 454,454,455
455 DO 457 LX=1,M
B(LX)=P(LX,IX,J)
457 CONTINUE
454 CONTINUE
WRITE(6,458) B(1),B(2),B(3),B(8),B(9),B(10),IL,IX
458 FORMAT(2X,'E=',F9.3,2X,'T0=',F9.3,2X,'U=',F9.3,2X,'P=',F9.3,
1 2X,'R0=',F9.6,2X,'T=',F9.3,4X,'IL=',I4,2X,'IX=',I4)
450 CONTINUE
RETURN
END

```

```

WRITE(6,10022)T08G
10022 FORMAT(1H0,3X,'T08G=',E15.7,3X,'AFTER SUBROUTINE INPUT')
DNP(2)=DNP(1)
WRITE(6,10012)DNP(2)
10012 FORMAT(1H0,3X,'DNP(2)='E12.6)
T2G=T02G
T6G=T06G
T5G=T02G
T10G=T08G
JV=0
501 II=0
CALL GASP(TIG, FN, GAMIG, CPIG, Z1, Z1, GMU)
IF (JCPRO .GE. 0)
1 PIG=R01*TIG/(.093178*GMU)
IF (JCPRO .LT. 0)
1 R01=.093178*PIG*GMU/TIG
WG=R01*VI*A(1)
FM1=WG*DSQRT(TIG/(GAMIG*GMU))/(20.7774*PIG*A(1))
T01G=TIG*(1.+FM1*FM1*(GAMIG-1.)/2.)
WRITE(6,198)R01,GMU,PIG,TIG
198 FORMAT(1H0,3X,'R01=',E15.7,5X,'GMU=',E15.7,5X,'PIG=',E15.7,
1 5X,'TIG=',E15.7)
T11G=T01G
10 DO 3 I=1,18
DO 4 J=1,18
4 AVT(I,J)=0.
3 GMT(I)=0.0
TPI=.5*(T2+T4)
TMII=.5*(T2+T6)
TMIII=.5*(T2+T7)
WIII=WII
TM=.5*(T3+T1)
Z1=T5G-T4
Z2=T6G-T2
IF (Z1 .LE. 0. .OR. Z2 .LE. 0.) GO TO 11
IF (Z1 .EQ. Z2) GO TO 12
TGM I=TM I+(Z1-Z2)/(DLOG(Z1)-DLOG(Z2))
GO TO 13
11 TGM I=.5*(T5G+T6G)
GO TO 13
12 TGM I=.5*(T5G+T6G)
13 Z1=T10G-T6
Z2=T11G-T2
IF (Z1 .LE. 0. .OR. Z2 .LE. 0.) GO TO 14
IF (Z1 .EQ. Z2) GO TO 15
TGM II=TM II+(Z1-Z2)/(DLOG(Z1)-DLOG(Z2))
GO TO 16
14 TGM II=.5*(T10G+T11G)
GO TO 16
15 TGM II=.5*(T10G+T11G)
16 Z1=T1-TA1
Z2=T3-TA2
IF (Z1 .LE. 0. .OR. Z2 .LE. 0.) GO TO 17
IF (Z1 .EQ. Z2) GO TO 18
TMA=TM-(Z1-Z2)/(DLOG(Z1)-DLOG(Z2))
GO TO 19

```

```

17 TMA=.5*(TA1+TA2)
   GO TO 1F
18 TMA=.5*(TA1+TA2)
19 CALL GASP(TGMI, FN, Z1, CPGI, PRGI, GIMU, GMU)
   Z1 = T7G-T7
   Z2 = T6G-T2
   IF(Z1 .LE. 0 .OR. Z2 .LE. 0) GO TO 20
   IF(Z1 .EQ. Z2) GO TO 21
   TGM3 = TMIII + (Z1-Z2)/(DLOG(Z1)-DLOG(Z2))
   GO TO 22
20 TGM3 = .5*(T7G+T3G)
   GO TO 22
21 TGM3 = .5*(T7G+T3G)
22 CONTINUE
   CALL GASP(TGMII, FN, Z1, CPGII, PRGII, GIIMU, GMU)
   CALL GASP(TGM3, FN, Z1, CPG3, PRG3, G3MU, GMU)
   WRITE(6,199)GIMU,GIIMU,VI
199  FORMAT(1H0,3X,'GIMU=',E15.7,5X,'GIIMU=',E15.7,5X,'VI=',E15.7)
   CALL AIRP(TA1, PAT, TYA, RH, PRA, AMU, CPA, Z1, AML)
   CALL LIGP(TMI, FG, ZIMU, PRI, CPI)
   CALL LIGP(TMII, FG, ZIIMU, PRII, CPII)
   CALL LIGP(TMIII, FG, Z3MU, PRIII, CPIII)
   CALL LIGP(TM, FG, ZMU, PR, CP)
   AFRGI=DL(1)*DH(1)
   AFRGII=DL(2)*DH(2)
   AFRA=DL(4)*DH(4)
   GGI=WC/(DSIG(1)*AFRGI)
   GGII=WC/(DSIG(2)*AFRGII)
   GGIII=GGII
   GA=WA/(DSIG(4)*AFRA)
   AFRI=DW(1)*DH(1)/DNP(1)
   AFRII=DW(2)*DH(2)/DNP(2)
   AFR=DW(4)*DH(4)/DNP(3)
   GI=W1/(DSI(1)*AFRI)
   GII=WII/(DSI(2)*AFRII)
   GIII=GI
   WRITE(6,10009)WII,DSI(2),AFRII
   WRITE(6,10010)DW(2),DH(2),DNP(2)
10009 FORMAT(1H0,3X,'WII=',E12.6,5X,'DSI(2)=' ,E12.6,5X,'AFRII=' ,E12.6)
10010 FORMAT(1H0,3X,'DW(2)=' ,E12.6,5X,'DH(2)=' ,E12.6,5X,'DNP(2)=' ,E12.6)
   W3=W1+WII+WB+WM+WV1+WV2+WE+WS
   G=W3/(DSI(4)*AFR)
   REGI=GGI*DDHG(1)/GIMU
   REGII=GGII*DDHG(2)/GIIMU
   REG3=REGII
   REA=GA*DDHG(4)/AMU
   REI=GI*DDH(1)/ZIMU
   REII=GI*DDH(2)/ZIIMU
   REIII=REII
   WRITE(6,10006)GI,II,GII,REI,REII
10006 FORMAT(1H0,3X,'GI=' ,E15.7,5X,'GII=' ,E15.7,5X,'REI=' ,E15.7,5X,
1 'REII=' ,E15.7)
   RE=G*DDH(4)/ZMU
   WRITE(6,197)REGI,REGII,REA,REI,REII,RE
197  FORMAT(1H0,3X,'REGI=' ,E13.6,4X,'REGII=' ,E13.6,4X,'REA=' ,E13.6,4X,
1 'REI=' ,E13.6,4X,'REII=' ,E13.6,4X,'RE=' ,E13.6)

```

```

Z1=DLOG(REGI)
Z2=-750.2946+629.2028*Z1-219.5279*Z1**2+40.7569*Z1**3-4.253034*Z1*
1*4+.2364432*Z1**5-.005466298*Z1**6
GFI=DEXP(Z2)
Z1=-360.4224+335.276*Z1-129.1436*Z1**2+26.20469*Z1**3-2.961196*Z1*
1*4+.1766745*Z1**5-.004345743*Z1**6
GJI=DEXP(Z1)
Z1=DLOG(REGII)
Z2=-750.2946+629.2028*Z1-219.5279*Z1**2+40.7569*Z1**3-4.253034*Z1*
1*4+.2364432*Z1**5-.005466298*Z1**6
GFII=DEXP(Z2)
GFIII=GFII
Z1=-360.4224+335.276*Z1-129.1436*Z1**2+26.20469*Z1**3-2.961196*Z1*
1*4+.1766745*Z1**5-.004345743*Z1**6
GJII=DEXP(Z1)
GJIII=GJII
Z1=DLOG(REA)
Z2=-7.652462+6.206772*Z1-1.715197*Z1**2+.1756196*Z1**3-.006207806*
1Z1**4
AF=DEXP(Z2)
Z1=2.123751-1.083736*Z1-.05205297*Z1**2+.01646661*Z1**3-.000782202
11*Z1**4
AJ=DEXP(Z1)
Z1=DLOG(REI)
Z1=-22.04452+12.84988*Z1-3.122052*Z1**2+.3159152*Z1**3-.01161237*Z
11**4
ZJI=DEXP(Z1)
Z1=DLOG(REII)
Z1=-22.04452+12.84988*Z1-3.122052*Z1**2+.3159152*Z1**3-.01161237*Z
11**4
ZJII=DEXP(Z1)
ZJII=ZJI
ZJIII=ZJII
Z1=DLOG(RE)
Z1=-22.04452+12.84988*Z1-3.122052*Z1**2+.3159152*Z1**3-.01161237*Z
11**4
ZJ=DEXP(Z1)
T03=-2./3.
HGI=GGI*CPGI*GJI*PRGI**T03
HGII=GGII*CPGII*GJII*PRGII**T03
HGIII=HGII
HA=GA*CPA*AJ*PRA**T03
HI=GI*CPI*ZJI*PRI**T03
HII=GII*CPII*ZJII*PRII**T03
HIII=HII
WRITE(6,10007)ZJII,CPII,PRII
10007 FORMAT(1H0,3X,'ZJII=',E15.7,5X,'CPII=',E15.7,5X,'PRII=',E15.7)
H=G*CP*ZJ*PR**T03
GMI=DSGRT(2.*HGI/(DK(1)*DDEL(1)))
GMII=DSGRT(2.*HGII/(DK(2)*DDEL(2)))
AM=DSGRT(2.*HA/(DK(3)*DDEL(4)))
T03=GVI*DSL(1)
ATFI=DTANH(T03)/T03
T03=GMII*DSL(2)
ATFII=DTANH(T03)/T03
T03=A*DSL(4)

```

```

ATFA=DTANH(TO3)/TO3
ATCI=1.-DAFOA(1)*(1.-ATFI)
ATOII=1.-DAFOA(2)*(1.-ATFII)
ATO=1.-DAFOA(4)*(1.-ATFA)
GM1=DSGRT(2.*HI/(DK(1)*DA(1)))
GM2=DSGRT(2.*HII/(DK(2)*DA(2)))
AMN=DSGRT(2.*H/(DK(3)*DA(4)))
TO3=GM1*DSLL(1)
ATF1L=DTANH(TO3)/TO3
TO3=GM2*DSLL(2)
ATF2L=DTANH(TO3)/TO3
TO3=AMN*DSLL(4)
ATFAL=DTANH(TO3)/TO3
ATO1=1.-DAFAL(1)*(1.-ATF1L)
ATO2=1.-DAFAL(2)*(1.-ATF2L)
ATOL=1.-DAFAL(4)*(1.-ATFAL)
UI=1./(1./(ATOI*HGI)+AB(1)/(DK(1)*(1.-DAFOA(1))))+DALG(1)/(DALF(1)*HI*ATO1))
UII=1./(1./(ATOII*HGII)+AB(2)/(DK(2)*(1.-DAFOA(2))))+DALG(2)/(DALF(12)*HI*ATO2))
UIII=UII
U=1./(1./(ATO*HA)+AB(4)/(DK(3)*(1.-DAFOA(3))))+DALG(4)/(DALF(4)*HI*1ATOL))
CGI=WG*CPGI
CGII=WG*CPGII
CGIII=CGII
CA=WA*CPA
CI=WI*CPI
CII=WII*CPII
CIII=CII
C=W3*CP
CMINI=DMIN1(CGI,CI)
CMAXI=DMAX1(CGI,CI)
CMINII=DMIN1(CGII,CII)
CMAXII=DMAX1(CGII,CII)
CMIN=DMIN1(CA,C)
CMAX=DMAX1(CA,C)
AGI=DL(1)*DH(1)*DW(1)*DALG(1)
AGII=DL(2)*DH(2)*DW(2)*DALG(2)
AGIII=AGII
AA=DL(4)*DH(4)*DW(4)*DALG(4)
TUNI=AGI*UI/CMINI
TUNII=AGII*UII/CMINII
TUN3=TUNII
TUN=AA*U/CMIN
TOWI=1.-DEXP(-TUNI*CMINI/(CMAXI*DNP(1)))
TOWII=1.-DEXP(-TUNII*CMINII/(CMAXII*DNP(2)))
TOW3=TOWII
TOW=1.-DEXP(-TUN*CMIN/(CMAX*DNP(3)))
ESSI=1.-DEXP(-TOWI*CMAXI/CMINI)
ESSII=1.-DEXP(-TOWII*CMAXII/CMINII)
ESS3=ESSII
ESS=1.-DEXP(-TOW*CMAX/CMIN)
IF (CMINI/CMAXI .GT. .9999) GO TO 31
EPSI=((1.-ESSI*CMINI/CMAXI)/(1.-ESSI))*NP(1)
EPSI=(EPSI-1.)/(EPSI-CMINI/CMAXI)

```



```

GO TO 32
31 EPSI=DNP(1)*ESSI/(1.+ESSI*(DNP(1)-1.))
32 IF (CMINII/CMAXII .GT. .9999) GO TO 33
   EPSII=((1.-ESSII*CMINII/CMAXII)/(1.-ESSII))*NP(2)
   EPSII=(EPSII-1.)/(EPSII-CMINII/CMAXII)
   EPS3=EPSII
   GO TO 34
33 EPSII=DNP(2)*ESSII/(1.+ESSII*(DNP(2)-1.))
   EPS3=EPSII
34 IF (CMIN/CMAX .GT. .9999) GO TO 35
   EPSA=((1.-ESS*CMIN/CMAX)/(1.-ESS))*NP(4)
   EPSA=(EPSA-1.)/(EPSA-CMIN/CMAX)
   GO TO 36
35 EPSA=DNP(4)*ESS/(1.+ESS*(DNP(4)-1.))
36 CONTINUE
   TO3=FM1*FM1
   PO1G=PIG*(1.+TO3*(GAMIG-1.)/2.)*(GAMIG/(GAMIG-1.))
   GO TO (30, 40, 50), NDSGN
C   CAVITY OPTION 1  CONST. MACH NUMBER
30 FM2=FM1
   A(2)=A(1)*(TO2G/TO1G)**((1.+GAMIG*TO3)/2.)
   GO TO 60
C   CAVITY OPTION 2  CONST. AREA
40 A(2)=A(1)
   Z1=TO1G*(1.+GAMIG*TO3)**2/(2.*(GAMIG+1.)*TO3*
1   (1.+TO3*(GAMIG-1.)/2.))
   Z1=TO2G/Z1
   IF (Z1 .GT. 1.) GO TO 10000
   I=0
12000 I=I+1
   CALL GASP(T2G, FN, GAM2G, CP2G, TO3, TO3, GMU)
   Z2 = 2.*GAM2G*Z1-2.*GAM2G-2.
   Z3=GAM2G*GAM2G*(Z1-1.)+1.
   IF (Z3 .NE. 0.) GO TO 41
   FM2=DSQRT(-Z1/Z2)
   GO TO 60
41 Z4=(-Z2+DSQRT(Z2*Z2-4.*Z1*Z3))/(2.*Z3)
   Z5=(-Z2-DSQRT(Z2*Z2-4.*Z1*Z3))/(2.*Z3)
   Z6=DMIN1(Z4, Z5)
   IF (Z6 .LT. 0.) Z6=DMAX1(Z4, Z5)
   WRITE(6,174)TO2G,TO3,PR
174 FORMAT(1H0,3X,'TO2G=',E15.7,5X,'TO3=',E15.7,5X,'PR=',E15.7)
   WRITE(6,173)Z1,Z2,Z3,Z4,Z5,Z6
173 FORMAT(1H0,3X,'Z1=',E15.7,5X,'Z2=',E15.7,5X,'Z3=',E15.7,5X,
1/,4X,'Z4=',E15.7,5X,'Z5=',E15.7,5X,'Z6=',E15.7)
   FM2=DSQRT(Z6)
   GO TO 60
C   CAVITY OPTION 3  GENERAL SHAPE
50 Z5=(GAMIG+GAM2G)/2.
   Z6=FM1*FM1
   N=NCS-1
   DO 51 J=1,N
   Z1=-2.*(1.+Z6*(Z5-1.)/2.)/(1.-Z6)
   Z2=(1.+Z5*Z6)*(-.5*Z1)
   Z3=(ACN(J+1)-ACN(J))/(2.*(ACN(J+1)+ACN(J)))
   Z4=(TO2G-TO1G)/((NCS-1.)*TO1G-(J-.5)*(TO2G-TO1G))

```

```

      Z6=Z6*(1.+Z3*Z1+Z2*Z4)
      IF (Z6 .LE. 1.) GO TO 51
10000 WRITE(K0,105)
      105 FORMAT(41H**** CHOKED CAVITY - READ NEW DATA *****)
      GO TO 2
      51 CONTINUE
      FM2=DSGRT(Z6)
      A(2)=ACN(NCS)
      60 T2GOLD=T2G
      T2G=TO2G/(1.+FM2*FM2*(GAM2G-1.)/2.)
      T2GDIF=T2GOLD-T2G
      IF(DABS(T2GDIF).LE..500) GO TO 11000
      IF(1.LE.NLIM) GO TO 12000
      PRINT 13000,1,T2GDIF
13000 FORMAT(58H****FAILURE TO CONVERGE IN STATIC TEMP. LOOP 1 - CYCLES
      '= ,I3,' - ERROR=',E12.5)
      GO TO 2
11000 WRITE(6,10050)GAM2G, GMU,T2G
10050 FORMAT (1H0,5X,'GAM2G = ', E15.7,3X,'GMU = ',E15.7,3X,'T2G = '
      1,E15.7,3X,'RIGHT BEFORE 11000',/)
      P2G=WG*DSGRT(T2G/(GAM2G*GMU))/(20.7774*A(2)*FM2)
      PO2G=P2G*(1.+FM2*FM2*(GAM2G-1.)/2.)*(GAM2G/(GAM2G-1.))
C   FIRST DIFFUSER
      PO3G=PO2G-CF23*(PO2G-P2G)
      FM3=FM2*A(2)/A(3)
      GAM3G=GAM2G
      CALL MACH(DELM, NLIM, PO3G, GAM3G, FM3, TO2G, WG, GMU,
      1 A(3), P3G, T3G, FN, CP3G)
C   SECOND DIFFUSER
      PO4G=PO3G-CF34*(PO3G-P3G)
      FM4=FM3*A(3)/A(4)
      GAM4G=GAM3G
      CALL MACH(DELM, NLIM, PO4G, GAM4G, FM4, TO2G, WG, GMU,
      1 A(4), P4G, T4G, FN, CP4G)
C   THIRPD DIFFUSER
      PO5G=PO4G-CF45*(PO4G-P4G)
      FM5=FM4*A(4)/A(5)
      GAM5G=GAM4G
      CALL MACH(DELM, NLIM, PO5G, GAM5G, FM5, TO2G, WG, GMU,
      1 A(5), P5G, T5G, FN, CP5G)
      RO5=.093178*P5G*GMU/T5G
      RO6=RO5
      FM6=WG*DSGRT(TO6G/GAM5G/GMU)/(20.7774*PO5G*A(6))
      I=0
      70 Z1=RO6
      PO6G=PO5G-GGI*GGI*((1.+DSIG(1)*DSIG(1))*(RO5/RO6-1.))+
      1 GFI*DALG(1)*DW(1)*RO5/(.5*DSIG(1)*(PO6+RO5))/
      2 (9266.11*RO5)
      GAM6G=GAM5G
      CALL MACH(DELM,NLIM,PO6G,GAM6G,FM6,TO6G,WG,GMU,A(6),P6G,T6G,FN,
      * CP6G)
      RO6=.093178*P6G*GMU/T6G
      I=I+1
      Z3=RO6-Z1
      IF (DABS(Z3) .LE. ROLIM) GO TO 71

```

```

      IF (I .LT. NLIM) GO TO 70
      WRITE(KO,101) Z3
101  FORMAT(53H**** FAILURE TO CONVERGE IN DENSITY LOOP 1 - ERROR = ,
1    E12.5,6H*****)
      71 CALL GASP(T07G, FN, GAM7G, CP7G, T03, T03, GMU)
      WRITE(KO,150) I, Z3
150  FORMAT(10X,'DENSITY LOOP 1 - CYCLES =',I3,' - ERROR =',E12.5)
      P07G=P06G*BPR
      J=0
      80 FM7=WG*DSQRT(T07G/(GAM7G*GMU))/(20.7774*P07G*A(7))
      CALL MACH(DELM, NLIM, P07G, GAM7G, FM7, T07G, WG, GMU,
1    A(7), P7G, T7G, FN, CP7G)
      R07=.093178*P7G*GMU/T7G
      R08=R07
      WRITE(6,10023)T03G
10023 FORMAT(1H0,3X,'T08G=',E15.7,3X,'FIRST USED IN A CALCULATION')
      FM8=WG*DSQRT(T08G/GAM7G/GMU)/(20.7774*P07G*A(7))
      I=0
10002 Z1=R08
      DW(4)=DW(1)
      DALG(4)=DALG(1)
      GGI11=GGI
      P08G=P07G-GGI11*GGI11*((1.+DSIG(1)*DSIG(1))*
1(R07/R08-1.))+GGI11*DALG(3)*DW(3)*P07/(.5*DSIG(3)*
2(R07+R08)))/(9256.11*R07)
      GAM8G=GAM7G
      WRITE(6,10001)P08G,GAM8G,FMS,T01G,WG
10001 FORMAT(1H0,3X,'P08G=',E15.7,5X,'GAM8G=',E15.7,5X,
1'FMS=',E15.7,5X,'T01G=',E15.7,5X,'WG=',E15.7)
      CALL MACH(DELM,NLIM,P08G,GAM8G,FMS,T03G,WG,GMU,A(3),
1P8G,T8G,FN,CP8G)
      R08=.093178*P8G*GMU/T8G
      I=I+1
      Z3=R08-Z1
      IF (DABS(Z3) .LE. ROLIM) GO TO 77
      IF (I .LT. NLIM) GO TO 10002
      WRITE (KO,10003)Z3
10003 FORMAT (53H****FAILURE TO CONVERGE IN DENSITY LOOP 3 - ERROR=,
1E12.5,6H*****)
77  CONTINUE
      CALL MACH(DELM, NLIM, P08G, GAM8G, FMS, T08G, WG, GMU,
1    A(8), P8G, T8G, FN, CP8G)
      P09G=P08G-CF89*(P08G-P8G)
      FM9=FM8*A(8)/A(9)
      GAM9G=GAM8G
      CALL MACH(DELM, NLIM, P09G, GAM9G, FM9, T08G, WG, GMU,
1    A(9), P9G, T9G, FN, CP9G)
      P010G=P09G-CF910*(P09G-P9G)
      FM10=FM9*A(9)/A(10)
      GAM10G=GAM9G
      CALL MACH(DELM, NLIM, P010G, GAM10G, FM10, T08G, WG, GMU,
1    A(10), P10G, T10G, FN, CP10G)
      R010=.093178*P10G*GMU/T10G
      R011=R010

```

```

      FM11=WG*DSQRT(T011G/GAM10G/GMU)/(20.7774*P010G*A(10))
      I=0
75  Z1=R011
      P011G=P010G-GGII*GGII*((1.+DSIG(2)*DSIG(2))*(R010/R011-1.)+
1   GFII*DALG(2)*DW(2)*R010/(.5*DSIG(2)*(R010+R011)))/
2   (9256.11*R010)
      GAM11G=GAM10G
      WRITE(6,183) P011G,GAM11G,FM11,T01G,WG
183  FORMAT(1H0,3X,'P011G=',E15.7,5X,'GAM11G=',E15.7,5X,'FM11=',
1E15.7,5X,'T01G=',E15.7,5X,'WG=',E15.7)
      CALL MACH(DELM,NLIM,P011G,GAM11G,FM11,T01G,WG,GMU,A(10),P11G,
* T11G,FN,CP11G)
      R011=.093178*P11G*GMU/T11G
      I=I+1
      Z3=R011-Z1
      IF (DABS(Z3) .LE. ROLIM) GO TO 76
      IF (I .LT. NLIM) GO TO 75
      WRITE(K0,120) Z3
120  FORMAT(53H***** FAILURE TO CONVERGE IN DENSITY LOOP 2 - ERROR = ,
1   E12.5,6H***** )
      Z6=FM11=WG*DSQRT(T01G/(GAM1G*GMU))/(20.7774*P011G*A(11))
      WRITE(K0,151) I, Z3
151  FORMAT(10X,'DENSITY LOOP 2 - CYCLES=',I3,' - ERROR =',E12.5)
      CALL MACH(DELM,NLIM,P011G,GAM11G,FM11,T01G,WG,GMU,
1   A(11), P11G, T11G,FN,CP11G)
      IF (JCPR0 .GE. 0)
1   Z1=P01*TIG/(.093178*GMU)*(1.+(GAM1G-1.)*FM1*FM1/2.)
2   *(GAM1G/(GAM1G-1.))
      Z1=P011G-CF111*(P011G-P11G)-Z1
      IF (JCPR0 .LT. 0)
1   Z1=P011G-CF111*(P011G-P11G)-P01G
      P011G=P011G-Z1
      P010G=P010G-Z1
      P09G=P09G-Z1
      P08G=P08G-Z1
      P07G=P07G-Z1
      CALL GASP(T6G,FN,GAM6G,CP6G,Z2,Z2,GMU)
      BPR=P07G/P06G
      Q6G=60.*A(6)*FM6*DSQRT(GAM6G*T6G*32.174*1545.43/GMU)
      ATAB=.730-7.09843*(DABS(Q6G/BRPM/NBS-.5355))*2.08014
      ATAB=0.6
      WRITE(6,186) Z1,P07G,P06G,Q6G
186  FORMAT(1H0,3X,'Z1=',E15.7,5X,'P07G=',E15.7,5X,'P06G=',E15.7,5X,
1   'Q6G=',E15.7)
      WRITE(6,187) T06G,BPR,GAM6G,ATAB
187  FORMAT(1H0,3X,'T06G=',E15.7,5X,'BPR=',E15.7,5X,'GAM6G=',E15.7,5X,
1   'ATAB=',E15.7)
      T07G=T06G*(BPR**((GAM6G-1.)/(ATAB*GAM6G)))
      WRITE(6,180) T06G,BPR,GAM6G,ATAB,T07G
180  FORMAT(1H0,3X,'T06G=',E15.7,5X,'BPR=',E15.7,5X,'GAM6G=',E15.7,5X,
1   'ATAB=',E15.7,5X,'T07G=',E15.7)
      J=J+1
      IF (DABS(Z1) .LT. PLIM) GO TO 85
      IF (J .LT. NLIM) GO TO 50

```

```

      WRITE(K0,103) Z1
103  FORMAT(52H**** FAILURE TO CONVERGE IN PRESSURE LOOP - ERROR = ,
1    E12.5,0H*****)
      85 CALL AIRP(TA1, PAT, TA1, RH, Z2, Z2, CPA1, Z2, AML)
      WRITE(K0,152) J, Z1
152  FORMAT(10X,'TOTAL PASSES THROUGH PRESSURE LOOP =',I3,
1    ' - ERROR =',E12.5)
      CALL AIRP(TA1, PAT, TA2, RH, Z1,Z1, CPA2, GAM2A, AML)
      CALL LIQP(T1, FG, Z1, Z1, CP1)
      CALL LIQP(T2, FG, Z1, Z1, CP2)
      CALL LIQP(T3, FG, Z1, Z1, CP3)
      CALL LIQP(T4, FG, Z1, Z1, CP4)
      CALL LIQP(T6, FG, Z1, Z1, CP6)
      CALL LIQP(T7, FG, Z1, Z1, CP7)
      CALL LIQP(T8, FG, Z1, Z1, CP8)
      CALL LIQP(T10, FG,Z1, Z1, CP10)
      CALL LIQP(T14, FG,Z1, Z1, CP14)
      CALL LIQP(T16, FG,Z1, Z1, CP16)
      CALL LIQP(T18, FG,Z1, Z1, CP18)
      CALL LIQP(T20, FG,Z1, Z1, CP20)
      WRITE(6,20000) CP2,CP6,FG,T2,T6
20000 FORMAT (1H0,3X,5F20.10)
      CMIN3=CMINII
      AMT(1,1)=WG*(CP1G+CP2G)/2.
      AMT(1,2)=-AMT(1,1)
      BMT(1)=QS-.948*PLKW*(1./EFFL-1.)
      AMT(2,2)=CGI
      AMT(2,3)=-AMT(2,2)
      AMT(2,6)=WI*.5*(CP2+CP4)
      AMT(2,8)=-AMT(2,6)
      AMT(3,2)=EPSI*CMINI-CGI
      AMT(3,6)=-EPSI*CMINI
      AMT(3,3)= CGI
      AMT(4,4)=1.
      AMT(4,3)=-(P07G/P06G)**((GAM6G-1.)/(ATAB*GAM6G))
      AMT(5,17)= CGII
      AMT(5,1)=-AMT(5,4)
      AMT(5,6)=WII*.5*(CP2+CP6)
      AMT(5,9)=-AMT(5,6)
      AMT(6,17)=EPSII*CMINII-CGII
      AMT(6,6)=-EPSII*CMINII
      AMT(6,1)=CGII
      AMT(7,7)=W3*.5*(CP1+CP3)
      AMT(7,5)=-AMT(7,7)
      AMT(7,16)=-CA
      BMT(7)=AMT(7,16)*TA1
      AMT(8,7)=EPSA*CMIN
      AMT(8,16)=-CA
      BMT(8)=(EPSA*CMIN-CA)*TA1
      AMT(9,5)=W3*.5*(CP1+CP2)
      AMT(9,6)=-AMT(9,5)
      BMT(9)=-QP
      AMT(10,8)=-WI*.5*(CP4+CP3)
      AMT(10,9)=-WII*.5*(CP6+CP3)

```



```

    AMT(10,13)=-WM*.5*(CP16+CP3)
    AMT(10,6)=-WB*.5*(CP2+CP3)
    AMT(10,10)=-WV1*.5*(CP8+CP3)
    AMT(10,11)=-WV2*.5*(CP10+CP3)
    AMT(10,14)=-WE*.5*(CP18+CP3)
    AMT(10,15)=-WS*.5*(CP20+CP3)
    AMT(10,7)=-AMT(10,8)-AMT(10,9)-AMT(10,13)-AMT(10,6)-AMT(10,10)-
*   AMT(10,11)-AMT(10,14)-AMT(10,15)
    AMT(11,6)=WM*.5*(CP2+CP14)
    AMT(11,12)=-AMT(11,6)
    BMT(11)=-GCM
    AMT(12,12)=WM*.5*(CP14+CP16)
    AMT(12,13)=-AMT(12,12)
    BMT(12)=-GM
    AMT(13,6)=WV1*.5*(CP2+CP8)
    AMT(13,10)=-AMT(13,6)
    BMT(13)=-QV1
    AMT(14,6)=WV2*.5*(CP2+CP10)
    AMT(14,11)=-AMT(14,6)
    BMT(14)=-QV2
    AMT(15,6)=WE*.5*(CP2+CP18)
    AMT(15,14)=-AMT(15,6)
    BMT(15)=-GE
    AMT(16,6)=WS*.5*(CP2+CP20)
    AMT(16,15)=-AMT(16,6)
    BMT(16)=-QS
    AMT(17,4)=CGIII
    AMT(17,5)=WIII*.5*(CP7+CP2)
    AMT(18,17)=CGIII
    AMT(17,17)=-CGIII
    AMT(17,18)=-WIII*.5*(CP7+CP2)
    AMT(18,4)=EPS3*(CMIN3)-CGIII
    AMT(18,18)=-EPS3*(CMIN3)
    CALL SIMQ(AMT, BMT, 18, KS)
    JJ=0
c  Z2=FM1
    TIG=BMT(1)/(1.+(GAMIG-1.)*FM1*FM1/2.)
    CALL GASP(TIG, FN, GAMIG, CFIG, Z1, Z1, GMU)
    IF (JCPR0 .GE. 0)
1    PIG=R01*TIG/(.093178*GMU)
    IF (JCPR0 .LT. 0)
1    R01=.093178*PIG*GMU/TIG
    WG=R01*VI*A(1)
    WRITE (6,10051) TIG, GAMIG, GMU
10051 FORMAT(1H0,5X,'TIG = ',E15.7,3X,'GAMIG = ',E15.7,3X,'GMU = ',E15.7
1,3X,'RIGHT AFTER WG=',//)
    FM1=WG*DSQRT(TIG/(GAMIG*GMU))/(20.7774*PIG*A(1))
    JJ=JJ+1
    Z3=Z2-FM1
    IF (DABS(Z3) .LT. DELM) GO TO 7
    IF (JJ .LT. NLIM) GO TO 6
    WRITE(KC,400) Z3
400 FORMAT(54H**** FAILURE TO CONVERGE IN FINAL MACH LOOP - ERROR = ,
1    E12.5,6H*****)

```

```

7 WRITE(KO,301) JJ, Z3
301 FORMAT(10X,'TOTAL PASSES IN FINAL MACH LOOP =',I3,' - ERROR =',
1 E12.5)
II=II+1
IF (KS .EQ. 1) GO TO 91
DO 93 KS=1,18
NN(KS)=-1
TDIF(KS)=SVR(KS)-BMT(KS)
IF (DABS(TDIF(KS)) .GT. CONV(KS)) NN(KS)=1
93 CONTINUE
WRITE(KO,201)
201 FORMAT(10X,'STATE VARIABLE ERRORS')
WRITE(KO,300) TDIF
300 FORMAT(10X,10E12.4)
WRITE(KO,153) II
153 FORMAT(10X,'END OF SIMQ PASS NO.',I3/)
CALL OUTPUT
IF (II .GT. N LIM) GO TO 92
DO 94 KS=1,18
IF (NN(KS) .GE. 0) GO TO 95
94 CONTINUE
GO TO 90
92 WRITE(KO,104)
104 FORMAT(40H**** FAILURE TO CONVERGE IN STATE VARIABLE LOOP*,
1 6H*****)
90 FM6=WG*DSQRT(T06G/(GAM6G*GMU))/(20.7774*P06G*A(6))
CALL MACH(DELM, NLIM, P06G, GAM6G, FM6, T06G, WG, GMU,
1 A(6), P6G, T6G, FN, CP6G)
FNBPB=DFLOAT(NBPB)
FNBS=DFLOAT(NBS)
DPSS=((P07G-P06G)*T06G*28.966)/(P06G*BRPM*BRPM*518.7*GMU*FNBPB)
DPSB=.8396-3.2323*(DABS(Q6G/(BRPM*FNBS)-.46875))*1.42327
DPSS=DPSS*1.E-9
ERR=DPSS-DPSS
GC=11.661E-7/(BRPM*FNBS)+11.589E-5*VIM**1.667/(BRPM*BRPM*FNBPB)
GC=ERR/GC
JV=JV+1
WRITE(KO,204) JV, GC
204 FORMAT(5X,'PASS NO.',I3,' THROUGH VELOCITY LOOP, CORRECTION =',
1 E12.5)
WRITE(6,175)Q6G,BRPM,FNBS
175 FORMAT(1H0,3X,'Q6G=',E15.7,5X,'BRPM=',E15.7,5X,'FNBS=',E15.7)
GC=0.0
IF (DABS(GC) .LE. V LIM) GO TO 502
IF (JV .GE. NLIM) GO TO 503
IF (GC .LT. 0. .AND. Q6G/(BRPM*FNBS) .LT. .46875) GO TO 504
506 CONTINUE
VIM=VIM+GC
VI=VIM*3.281
GO TO 501
504 WRITE(KO,205)
205 FORMAT(50H**** BLOWERS ARE CHOKED - PROCESS NEXT CASE *****)

```

```

      GO TO 2
503 WRITE(K0,203) GC
203 FORMAT(52H**** FAILURE TO CONVERGE IN VELOCITY LOOP - ERROR = ,
1   E12.5,6H*****)
502 CONTINUE
      T03G=T02G
      T04G=T02G
      T05G=T02G
      T09G=T08G
      T010G=T08G
      T011G=T01G
      BLPR=WG*.5*(CP6G+CP7G)*T06G*(BPR**((1.-2./(GAM6G+GAM7G))
1   /ATAB)-1.)*778./550.
      BLPRM=BLPR*.7457
      DPI=4.317E-4*GI*GI*FI*DL(1)*DNP(1)/(ROLI*DDH(1))
      DPII=4.317E-4*GII*GII*FII*DL(2)*DNP(2)/(ROLII*DDH(2))
      DPIII=DPII
      DP=4.317E-4*G*G*F*DL(4)*DNP(3)/(ROL*DDH(4))
      ROA1=144.*PAT*AML/(1545.32*TA1)
      ROA2=ROA1
      LL=0
27  Z1=ROA2
      PA2=PAT-GA*GA*((1.+DSIG(4)**2)*(ROA1/ROA2-1.))+
1   AF*DALG(4)*DW(4)*ROA1/(.5*DSIG(4)*(ROA1+ROA2)))/
2   (ROA1*2.*32.174*144.)
      ROA2=144.*PA2*AML/(1545.32*TA2)
      LL=LL+1
      Z3=ROA2-Z1
      IF (DABS(Z3) .LT. ROLIM) GO TO 38
      IF (LL .LE. NLIH) GO TO 37
      WRITE(K0,401) Z3
401 FORMAT(49H**** FAILURE TO CONVERGE IN AUX. DENSITY LOOP - *,
1   'ERROR =',E12.5,6H*****)
      GO TO 39
38  WRITE(K0,202) LL, Z3
202 FORMAT(10X,'TOTAL PASSES THROUGH AUX. DENSITY LOOP =',I3,
1   ' - ERROR =',E12.5)
39  PF=WA*CPA2*TA2*778./550.
      WRITE(6,10004)GAM2A,ATAP
10004 FORMAT(1H0,3X,'GAM2A=',E15.7,5X,'ATAP=',E15.7)
      PFM=.7457*PF
      RO6G=.093178*P6G*GMU/T6G
      ICORR=60.*WG*DSQRT(1.4*GMU*513.7/(GAM6G*28.97*T06G))/RO6G
      DO 99 KS=1,16
99  SVR(KS)=BMT(KS)
      QDI=WI*1800.*(CP2+CP4)*(T4-T2)
      QDII=WII*1800.*(CP2+CP6)*(T6-T2)
      QDIII=QDII
      WRITE (6,10005)CP2,CP6,T6,T2,WII
10005 FORMAT(1H0,3X,'CP2=',E15.7,5X,'CP6=',E15.7,5X,'T6=',E15.7,5X,
1   'T2=',E15.7,5X,'WII=',E12.6)

```

```

      WRITE(6,10011)CP4,T4,WI
10011 FORMAT(1H0,3X,'CP4=',E15.7,5X,'T4=',E15.7,5X,'WI=',E12.6)
      GDA=W3*1800.*(CP3+CP1)*(T3-T1)
      WRITE(K0,20005)GDII,GDA
20005 FORMAT (1H0,3X,'GDII=',E12.6,5X,'GDA=',E12.6)
      CALL OUTPUT
      GO TO 2
    95 DO 96 KS=1,18
    96 SVR(KS)=BMT(KS)
      GO TO 10
    91 WRITE(K0,102)
102  FORMAT(' SINGULAR MATRIX')
      GO TO 2
      END

```

```

SUBROUTINE ENPUT
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION SVR(19)
DIMENSION ESVR(18)
COMMON /VAR/ T01G, T02G, T06G, T07G, T1, T2, T3, T4, T6, T8,
A T10, T14, T16, T18, T20, TA2, T08G, T7,
B T03G, T04G, T05G, T09G, T010G, T011G, T5, T9, T11,
C T12, T13, T15, T17, T19, T1G, T2G, T3G, T4G, T5G, T6G, T7G,
D T8G, T9G, T10G, T11G, TA1, EFFL, P01G, P02G, P03G, P04G, P05G,
E P06G, P07G, P08G, P09G, P010G, P011G, P1G, P2G, P3G, P4G, P5G,
F P6G, P7G, P8G, P9G, P10G, P11G, P(20), AC(20), VC(20), FM1,
G FM2, FM3, FM4, FM5, FM6, FM7, FM8, FM9, FM10, FM11, A(11),
H GAM1G, GAM2G, GAM3G, GAM4G, GAM5G, GAM6G, GAM7G, GAM8G, GAM9G,
I GAM10G, GAM11G, TGM1, TGMII, TMG3, TMA, GIMU, GIIMU, G3MU, AMU,
J PRGI,
K PRGII, PRG3, PRA, CPGI, CPGII, CPG3, CPA, TMI, TMII, TMIII, TM,
L ZIMU, ZIIMU, Z3MU, ZMU,
M PRI, PRII, PRIII, PR, CPI, CPII, CPIII, CP, GGI, GGII, GGIII,
1 GA, GI, GII, GIII, G, REGI,
2 REGII, REG3, REA, REI, REII, REIII, RE, GFI, GFII, GFIII,
COMMON/VARB/
N GJII, GJIII, AJ, ZJI, ZJII, ZJIII, ZJ, HGI, HGII, HGIII, HA,
1 HI, HII, HIII, H, CGI, CGII, CGIII,
N CA, CI, CII, CIII, C, UI, UII, UIII, U, AGI, AGII, AGIII, AA,
1 TUNI, TUNII, TUNIII, TUN,
O TOWI, TOWII, TOW3, TOW, EPSI, EPSII, EPS3, EPSA, ESSI, ESSII,
1 ESS3, ESS, WG,
P Q5G, QCORR, BPR, ALT, PAT, PA2, RH, FN(4), EFFLP, VI, VIM,
Q PIGA, HIM, CLIM, WTIM, DCM, BLPR, BLPRM, CPP, CPM, PF, PFM,
R R01, PLKW, WI, WII, WIII, WB, WM, WV1, WV2, WE, WS, WA, QP, QCM,
S GX, QV1, QV2, QE, QS, CF34, CF45, CF78, CF89, CF910,
COMMON /VARC/CF111, ATAP, H1, CL1, WT1, ACN(20), DC, DL(4),
A DH(4), DW(4), DDHG(4), DALG(4), DAFOA(4), DSIG(4), DDEL(4),

```

```

B DA(4), DK(3), DSL(4), DSI(4), DALF(4), DDH(4), CONV(16), DELM,
C ROLIM, PLIM, FG, TITLE(28), DP, DPI, DPII, DPIII, PPR, PPRM,
D TA1F, RHP, TIGM, DKH(4), ETIG, ET02G, ET06G, ET07G, ET1,
E ET2, ET3, ET4, ET6, ET8, ET10, ET14, ET16, ET18, ET20, ETA2,
1 ET08G, ET7,
F ESPP, CWA, DNP(3), GDI, GDII, GDIII,
1 GDA, EVIM, BRPM, VLIM, ROA1,
G ROA2, DAFAL(4), DSLL(4), AB(4)
COMMON /IVAR/ NTAM, NDSGN, NCS, KI, KO, NLIM, NP(4), NFULL,
1 NBS, NBPS, JCPRC

```

C

```

EQUIVALENCE (ESVR(1), ETIG)
EQUIVALENCE (SVR(1), T01G)
NAMELIST /FPT/ NTAM, TA1F, PLKW, ETIG, ET02G, ET06G, ET07G, ET1,
A ET2, ET3, ET4, ET6, ETA2, ET14, ET16, ET8, ET10, ET18, ET20,
B EFFLP, WI, WII, WIII, WB, WM, WV1, WV2, WE, WS, CWA,
C GP, GCM, GM, GV1, GV2, QE, QS, CF23, CF34,
D CF45, CF78, CF89, CF910, CF111,
E EVIM, ATAP, FIGA, H1M, CL1M, WT1M, FN, ACN, DCM,
F DL, DH, DW, DDHG, DALG, DAFOA, DSIG, DDEL,
G DA, DKH, DSL, DSI, DALF, DDH, NP,
H PAT, RHP, ESPP, A, CONV, DELM, NDSGN, NCS,
I NLIM, ROLIM, PLIM, FG, BRPM, VLIM, NBS, NBPS, JCPRC, RO1,
J DAFAL, DSLL, AB

```

C

```

KI=5
KO=6
READ(KI,200) (TITLE(J),J=1,14)
READ(KI,200) (TITLE(J),J=15,28)
200 FORMAT(13A6,A2)
READ(KI,FPT)
TA1=TA1F+459.69
TIG=TA1
T02G=TA1+210.
T06G=TA1+30.
T07G=TA1+70.
T1=TA1+20.
T2=TA1+20.
T3=TA1+40.
T4=TA1+55.
T6=TA1+30.
T8=TA1+65.
T10=TA1+65.
T14=TA1+30.
T16=TA1+75.
T18=TA1+65.
T20=TA1+65.
TA2=TA1+30.
T7=TA1+20.
BPR=1.17
VIM=120.
DO 30 K=1,16
30 IF (ESVR(K) .GT. 0.) SVR(K)=ESVR(K)

```



```

WRITE(6,10026)SVR(1),SVR(2),SVR(3),SVR(4),SVR(15),SVR(16),SVR(17),
1SVR(18),SVR(19)
10026 FORMAT(1H0,3X,'SVR(1)=' ,E15.7,5X,'SVR(2)=' ,E15.7,5X,'SVR(3)=' ,E15.
17,5X,'SVR(4)=' ,E15.7,7/4X,'SVR(15)=' ,E15.7,5X,'SVR(16)=' ,E15.7,7/
25X,'SVR(17)=' ,E15.7,5X,'SVR(18)=' ,E15.7,5X,'SVR(19)=' ,E15.7)
IF (EBPR .GT. 0.) BPR=EBPR
IF (EVIM .GT. 0.) VIM=EVIM
IF (NTAM .LT. 0) CALL EXIT
IF (NTAM .LE. 0) GO TO 10
DO 20 J=1,19
20 SVR(J)=TA1
10 CONTINUE
PIG=PIGA*14.7
RH=RHP*.01
EFFL=EFFLP*.01
VI=VIM*3.281
DC=DCM*.03281
H1=H1M*.03281
WT1=WT1M*.03281
CL1=CL1M*.03281
CALL AIRP(TA1, PAT, TA1, RH, X, X, X, X, AML)
ROA1=PAT*AML*.09317/TA1
WA=ROA1*CWA*DSGRT(TA1/518.7)/60.
DK(1) = DKH(1)/3600.
DK(2) = DKH(2)/3600.
DK(3) = DKH(4)/3600.
DNP(1)=NP(1)
DNP(2)=NP(2)
DNP(3)=NP(4)
A(1)=H1*CL1
Q6G=VI*A(1)*60.
WRITE(KO,102)
102 FORMAT('1')
WRITE(KO,FPT)
101 FORMAT(21X,14A6)
WRITE(KO,101) TITLE
RETURN
END

```

```

SUBROUTINE GASP(T, FN, GAM, CP, PR, UM, GMU )
IMPLICIT REAL*8 (A-H,C-Z)
DIMENSION FN(4), WM(4), TB(4), C(4), U(4), FK(4),
1 G(4), X(4), CN(4), S(4)
C 1 = HE
C 2 = N2
C 3 = CO2
C 4 = CO
DATA TB /4.215D0,77.4D0,194.66D0,81.5D0/

```

```

C      DATA WM /4.0000,28.0160, 44.0100, 28.0100/ , R /1.986460/
C      C(1) = 1.2406
C      IF (T .LE. 650.)
1      FK(1)=(.8+(T-475.)*( .97-.8)/175.)*.1
      IF (T .GT. 650.)
1      FK(1)=(.97+(T-650.)*(1.13-.97)/200.)*.1
      FK(1)=FK(1)/3600.
C
C      G(1)=1.6667
C      U(1)=1.12+(T-400.)*(1.955-1.12)/500.
      U(1)=U(1)*1.E-5
C
C      IF (T .LE. 600)
1      C(2)=3.502+(T-400.)*(3.5065-3.502)/200.
      IF (T .GT. 600. .AND. T .LE. 800.)
1      C(2)=3.5065+(T-600.)*(3.5315-3.5065)/200.
      IF (T .GT. 800.)
1      C(2)=3.5315+(T-800.)*(3.559-3.5315)/100.
      C(2)=C(2)*R/WM(2)
C
C      IF (T .LE. 650.)
1      FK(2)=.925+(T-450.)*(1.265-.925)/200.
      IF (T .GT. 650.)
1      FK(2)=1.265+(T-650.)*(1.573-1.265)/200.
      FK(2)=FK(2)*1.4E-2/3600.
C
C      G(2)=1.4
      IF (T .GT. 600.)
1      G(2)=1.4+(T-600.)*(1.391-1.4)/300.
C
C      IF (T .LE. 550.)
1      U(2)=.933+(T-450.)*(1.087-.933)/100.
      IF (T .GT. 550. .AND. T .LE. 725.)
1      U(2)=1.087+(T-550.)*(1.33-1.087)/175.
      IF (T .GT. 725)
1      U(2)=1.33+(T-725.)*(1.545-1.33)/175.
      U(2)=U(2)*1.1172E-5
C
C      IF (T .LE. 600.)
1      C(3)=4.195+(T-450.)*(4.653-4.195)/150.
      IF (T .GT. 600. .AND. T .LE. 750.)
1      C(3)=4.653+(T-600.)*(5.045-4.653)/150.
      IF (T .GT. 750.)
1      C(3)=5.045+(T-750.)*(5.365-5.045)/150.
      C(3)=C(3)*R/WM(3)
C

```

```

      IF (T .LE. 500.)
1     FK(3)=.82+(T-425.)*(1.32-.82)/175.
      IF(T.LE.140.)FK(3)=5.714E-3
      IF (T .GT. 500.)
1     FK(3)=1.32+(T-600.)*(2.12-1.32)/250.
      FK(3)=FK(3)*8.407E-3/3600.

C
      IF (T .LE. 450.)
1     G(3)=1.334+(T-400.)*(1.315-1.334)/50.
      IF (T .GT. 450. .AND. T .LE. 550.)
1     G(3)=1.315+(T-450.)*(1.286-1.315)/100.
      IF (T .GT. 550. .AND. T .LE. 650.)
1     G(3)=1.286+(T-550.)*(1.2645-1.286)/100.
      IF (T .GT. 650. .AND. T .LE. 750.)
1     G(3)=1.2645+(T-650.)*(1.248-1.2645)/100.
      IF (T .GT. 750. .AND. T .LE. 850.)
1     G(3)=1.248+(T-750.)*(1.235-1.248)/100.
      IF (T .GT. 850.)
1     G(3)=1.235+(T-850.)*(1.2295-1.235)/50.

C
      IF (T .LE. 575.)
1     U(3)=.9175+(T-450.)*(1.152-.9175)/125.
      IF (T .GT. 575. .AND. T .LE. 700.)
1     U(3)=1.152+(T-575.)*(1.375-1.152)/125.
      IF (T .GT. 700.)
1     U(3)=1.375+(T-700.)*(1.541-1.375)/100.
      U(3)=U(3)*9.2067E-6

C
      FT=FN(1)+FN(2)+FN(3)
      NGAS=3
      IF (FN(4) .LE. 0.) GO TO 10
      FT=FT+FN(4)
      NGAS=4

C
      IF (T .LE. 540.)
1     C(4)=3.503+(T-400.)*(3.506-3.503)/140.
      IF (T .GT. 540. .AND. T .LE. 630.)
1     C(4)=3.506+(T-540.)*(3.513-3.506)/90.
      IF (T .GT. 630. .AND. T .LE. 720.)
1     C(4)=3.513+(T-630.)*(3.529-3.513)/90.
      IF (T .GT. 720. .AND. T .LE. 810.)
1     C(4)=3.529+(T-720.)*(3.552-3.529)/90.
      IF (T .GT. 810.)
1     C(4)=3.552+(T-810.)*(3.583-3.552)/90.
      C(4)=C(4)*.0708989

C
      IF (T .LE. 540.)
1     U(4)=.84+(T-400.)*(1.075-.84)/140.
      IF (T .GT. 540. .AND. T .LE. 720.)
1     U(4)=1.075+(T-540.)*(1.34-1.075)/180.
      IF (T .GT. 720.)
1     U(4)=1.34+(T-720.)*(1.575-1.34)/180.
      U(4)=U(4)*1.1132E-5

C

```

```

      IF (T .LE. 530.)
1    G(4)=1.4
      IF (T .GT. 530.)
1    G(4)=1.4+(T-530.)*(1.3885-1.4)/370.

      IF (T .LE. 540.)
1    FK(4)=.825+(T-400.)*(1.087-.825)/140.
      IF (T .GT. 540. .AND. T .LE. 720.)
1    FK(4)=1.087+(T-540.)*(1.385-1.087)/180.
      IF (T .GT. 720.)
1    FK(4)=1.385+(T-720.)*(1.665-1.385)/180.
      FK(4)=FK(4)*.01342/3600.

```

```

C
C
10  CP=0.
    DAM=0.
    GAM=0.
    UM=0.
    GMU=0.
    Z3=0.
    DO 11 I=1,NGAS
      S(I)=1.5*TB(I)*1.8
      X(I)=FN(I)/FT
11  GMU=GMU+X(I)*WM(I)
    DO 50 I=1,NGAS
      CN(I)=X(I)*WM(I)/GMU
      CP=CP+CN(I)*C(I)
      GAM=CN(I)*C(I)+GAM
      DAM=CN(I)*C(I)/G(I)+DAM
      Z1=0.
      Z2=0.
      DO 30 J=1,NGAS
        IF (J .NE. I) GO TO 12
        P=1.
        AM=1.
        GO TO 29
12  D=X(J)/X(I)
      E=DSQRT(S(I)*S(J))
      UR=U(I)/U(J)
      WR1=DSQRT(8.*(1.+WM(I)/WM(J)))
      WR=(WM(J)/WM(I))**.25
      P=D*(1.+DSQRT(UR)*WR)**2/WR1
      AM=.25*D*(1.+DSQRT(UR*WR)**3*(T+S(I))/(T+S(J))))**2*(T+E)/(T+S(I))
29  Z1=Z1+P
      Z2=Z2+AM
30  CONTINUE
      Z3=Z3+FK(I)/Z2
      UM=UM+U(I)/Z1
50  CONTINUE
      GAM=GAM/DAM
      PR=CP*UM/Z3
      RETURN
      END

```

```

SUBROUTINE MACH(DELM, NLM, POG, GAM, FM, TOG, WG, GMU, A, PG,
1 TG, FN, CP)
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION FN(4)
DATA KO /6/
I=0
10 FMG=FM
TG=1.+FMG*FMG*(GAM-1.)/2.
WRITE(6,11)POG,TG,GAM
11 FORMAT(1H0,3X,'POG=',E15.7,5X,'TG=',E15.7,5X,'GAM=',E15.7)
PG=POG/TG**((GAM/(GAM-1.))
TG=TOG/TG
FM=WG*DSQRT(TG/(GAM*GMU))/(20.7774*PG*A)
WRITE(6,12)PG,TG,FM
12 FORMAT(1H0,3X,'PG=',E15.7,5X,'TG=',E15.7,5X,'FM=',E15.7)
CALL GASP(TG, FN, GAM, CP, DUM, DUM, GMU)
I=I+1
FMG1=FMG-FM
IF (DABS(FMG1) .LT. DELM) RETURN
IF (I .LT. NLM) GO TO 10
WRITE(KO,100) FMG1
100 FORMAT('          FAILURE TO CONVERGE IN MACH NO. SUBROUTINE',
1 ' - ERROR =',E12.5)
RETURN
END

```

```

SUBROUTINE AIRP(TAMB, PAMB, T, RH, P, AMU, CPA, GAM, AML)
IMPLICIT REAL*8 (A-H, O-Z)
T2=DEXP(-38.09873+.1057402*TAMB-.674864E-4*TAMB*TAMB)
WF=RH*18.016*T2/(28.966*(PAMB-T2))
T2=T*T
P=.5552+.134633E-2*T-.031E-4*T2+.20666E-8*T*T2
AMU=1.E-5+.175E-7*(T-400.)
CPA=.2421-.0015E-2*T+2.E-8*T2
GAMA=CPA/(CPA-.0685545)
CPW=.4509-.0054E-2*T+.0008E-4*T2
GAMW=CPW/(CPW-.11022)
A=WF*CPW
B=(1.-WF)*CPA
CPA=WF*CPW+(1.-WF)*CPA
GAM=(A+B)/(A/GAMW+B/GAMA)
AML=18.016*WF+28.966*(1.-WF)
RETURN
END

```





```

      IJ=IT+1
      IF (DABS(BIGA)-DABS(A(IJ))) 20,30,30
20  BIGA=A(IJ)
      IMAX=I
30  CONTINUE
C
C      TEST FOR PIVOT LESS THAN TOLERANCE (SINGULAR MATRIX)
C
      IF (DABS(BIGA)-TOL) 35, 35, 40
35  KS=1
      RETURN
C
C      INTERCHANGE ROWS IF NECESSARY
C
40  I1=J+N*(J-2)
      IT=IMAX-J
      DO 50 K=J,N
          I1=I1+N
          I2=I1+IT
          SAVE=A(I1)
          A(I1)=A(I2)
          A(I2)=SAVE
C
C      DIVIDE EQUATION BY LEADING COEFFICIENT
C
50  A(I1)=A(I1)/BIGA
      SAVE=B(IMAX)
      B(IMAX)=B(J)
      B(J)=SAVE/BIGA
C
C      ELIMINATE NEXT VARIABLE
C
      IF (J-N) 55, 70, 55
55  IGS=N*(J-1)
      DO 55 IX=JY,N
          IXJ=IGS+IX
          IT=J-IX
          DO 60 JX=JY,N
              IXJX=N*(JX-1)+IX
              JJX=IXJX+IT
60  A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))
65  B(IX)=B(IX)-(B(J)*A(IXJ))
C
C      BACK SOLUTION
C
70  NY=N-1
      IT=N*N
      DO 80 J=1,NY
          IA=IT-J
          IB=N-J

```

```

      IC=N
      DO 30 K=1,J
      B(13)=B(13)-A(1A)*B(1C)
      1A=1A-N
30    IC=IC-1
      RETURN
      END

```

```

SUBROUTINE OUTPUT
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION QC(11), QCG(11), DPC(11), DPCR(11)
DIMENSION VG(11), GG(11), PP(11), PC(11), ROG(11)
COMMON /VAR/ T01G, T02G, T06G, T07G, T1, T2, T3, T4, T6, T8,
A  T10, T14, T16, T18, T20, TA2, T08G, T7,
B  T03G, T04G, T05G, T09G, T010G, T011G, T5, T9, T11,
C  T12, T13, T15, T17, T19, T1G, T2G, T3G, T4G, T5G, T6G, T7G,
D  T8G, T9G, T10G, T11G, TA1, EFEL, P01G, P02G, P03G, P04G, P05G,
E  P06G, P07G, P08G, P09G, P010G, P011G, P1G, P2G, P3G, P4G, P5G,
F  P6G, P7G, P8G, P9G, P10G, P11G, P(20), AC(20), VC(20), FM1,
G  FM2, FM3, FM4, FM5, FM6, FM7, FM8, FM9, FM10, FM11, A(11),
H  GAM1G, GAM2G, GAM3G, GAM4G, GAM5G, GAM6G, GAM7G, GAM8G, GAM9G,
I  GAM10G, GAM11G, TGM1, TGM2, TGM3, TMA, GIMU, GIIMU, G3MU, AMU,
1  PRG1,
J  PRG2, PRG3, PRA, CPG1, CPG2, CPG3, CPA, TMI, TM2, TM3, TM,
1  ZIMU, ZIIMU, Z3MU, ZMU,
K  PRI, PRII, PRIII, PR, CPI, CPII, CPIII, CP, GGI, GGII, GGIII,
1GA, GI, GII, GIII, G, REG1,
L  REG2, REG3, REA, REI, REII, REIII, RE, GFI, GFII, GFIII,
COMMON/VARB/
AF, FI, FII, F, GJI,
M  GJII, GJIII, AJ, ZJI, ZJII, ZJIII, ZJ, HGI, HGII, HGIII, HA,
1  HI, HII, HIII, H, CGI, CGII, CGIII,
N  CA, CI, CII, CIII, C, UI, UII, UIII, U, AGI, AGII, AGIII, AA,
1  TUNI, TUNII, TUNIII, TUN,
O  TOWI, TOWII, TOW3, TOW, EPSI, EPSII, EPS3, EPSA, ESSI, ESSII,
1  ESS3, ESS, WG,
P  Q6G, GCORR, BPR, ALT, PAT, PA2, RH, FN(4), EFELP, VI, VIM,
Q  FIGA, HIM, CLIM, WTIM, DCM, BLPR, BLPRM, CPP, CPPM, PF, PFM,
R  RO1, PLKW, WI, WII, WIII, WB, WM, WV1, WV2, WE, WS, WA, GP, QCM,
S  QM, Qy1, QV2, GE, QS, CF23, CF34, CF45, CF78, CF89, CF910,
COMMON /VARC/CF111, ATAP, H1, CL1, WT1, ACN(20), DC, DL(4),
A  DH(4), DW(4), DDHG(4), DALG(4), DAFOA(4), DSIG(4), DDEL(4),
B  DA(4), DK(3), DSL(4), DSI(4), DALF(4), DDH(4), CONV(16), DELM,
C  ROLIM, PLIM, FG, TITLE(28), DP, DPI, DPII, DPIII, PPR, PPRM,
D  TA1F, RHP, TIGM, DKH(4), ETIG, ET02G, ET06G, ET07G, ET1,
E  ET2, ET3, ET4, ET6, ET8, ET10, ET14, ET15, ET18, ET20, ETA2,
1  ET08G, ET7,
F  EBRP, CWA, DNP(3), QDI, QDII, QDIII,
1  QDA, FVIM, BRPM, VLIM, ROA1,
G  ROA2, DAFAL(4), DSL(4), AB(4)
COMMON/VARD/QC,QCG,CP2,CP6,W3,CP3,CP1,FIII,TUN3
COMMON /IVAR/ NTAM, NDSGN, NCS, KI, KO, NLIW, NP(4), NFULL,
1  NES, NEPS, JCPRO

```

```

WRITE(KO,10028)WII,CP2,CP6,T6,T2,W3,CP3,CP1,T3,T1
10023 FORMAT (1H0,3X,'WII=',E12.6,5X,'CP2=',E15.7,5X,'CP6=',E15.7,5X,
1'T6=',E15.7,7/4X,'T2=',E15.7,5X,'W3=',E12.6,5X,'CP3=',E15.7,5X,
2'CP1=',E15.7,7/4X,'T3=',E15.7,5X,'T1=',E15.7)
WRITE(KO,10029)GDII,GDA
10029 FORMAT (1H0,3X,'GDII=',E12.6,5X,'GDA=',E12.6)
WRITE(KO,100)
WRITE(KO,101) TITLE
WRITE(KO,400)
400 FORMAT('0 INPUT LIST'/' CAVITY * LASER SPECIFICATIONS'/
1 ' DESCRIPTION',24X,' NAME VALUE UNITS')
WRITE(KO,403) PIGA
403 FORMAT(' INLET PRESSURE ',12(' '), 'PIGA ',G12.6,' ATM')
WRITE(KO,404) H1M
404 FORMAT(' INLET HEIGHT ',13(' '), 'H1M ',G12.6,' CM')
WRITE(KO,405) WT1M
405 FORMAT(' WIDTH IN FLOW DIRECTION ',8(' '), 'WT1M ',G12.6,
1 ' CM')
WRITE(KO,406) CL1M
406 FORMAT(' LENGTH ',16(' '), 'CL1M ',G12.6,' CM')
WRITE(KO,408) DCM
408 FORMAT(' INLET HYDRAULIC DIAMETER ',7(' '), 'DCM ',G12.6,
1 ' CM')
WRITE(KO,407) PLKW
407 FORMAT(' LASER OUTPUT POWER . . ',8(' '), 'PLKW ',G12.6,
1 ' KW')
WRITE(KO,401) EFFLP
401 FORMAT(' LASER EFFICIENCY ',11(' '), 'EFFLP ',G12.6,
1 ' PERCENT')
WRITE(KO,409) NDSGN
409 FORMAT(' DESIGN OPTION ',13(' '), 'NDSGN ',I7,5X,' -')
IF (NDSGN.NE. 3) GO TO 50
WRITE(KO,410) NCS
410 FORMAT(' NUMBER OF AREAS (NDSGN=3) ',7(' '), 'NCS ',
1 I7,5X,' -')
WRITE(KO,411) (ACN(K),K=1,NCS)
411 FORMAT(' AREAS ',17(' '), 'ACN ',6(G12.6,1X),
1 3(51X,6(G12.6,1X)))
WRITE(KO,412)
412 FORMAT(65X,'FT**2')
50 WRITE(KO,413) FN
413 FORMAT(' GAS MIXTURE ',14(' '), 'FN ',4F6.2,
1 ' HE TO N2 TO CO2 TO CO')
WRITE(KO,414)
414 FORMAT('0INITIAL ESTIMATE OF STEADY STATE QUANTITIES',
1 36X,'IF = 0.,USES')
WRITE(KO,415) ETIG
415 FORMAT(' GAS STATIC TEMPERATURE - STATION 1',3(' '), 'ETIG ',
1 G12.6,' DEG R',10X,'TA1 + 20.')
WRITE(KO,416) ET02G
416 FORMAT(' GAS TOTAL TEMPERATURE - STATION 2 ',3(' '), 'ET02G ',
1 G12.6,' DEG R',10X,'TA1 + 210.')
WRITE(KO,417) ET06G

```

```

417 FORMAT('      GAS TOTAL TEMPERATURE - STATION 6 ',3(' '), 'ET06G ',
1  G12.6, ' DEG R',10X, 'TA1 + 30. ')
WRITE(K0,418) ET07G
418 FORMAT('      GAS TOTAL TEMPERATURE - STATION 7 ',3(' '), 'ET07G ',
1  G12.6, ' DEG R',10X, 'TA1 + 70. ')
WRITE(K0,419) ET1
WRITE(K0,420) ET2
WRITE(K0,421) ET3
WRITE(K0,422) ET4
WRITE(K0,423) ET6
WRITE(K0,424) ET3
WRITE(K0,425) ET10
WRITE(K0,426) ET14
WRITE(K0,427) ET16
WRITE(K0,428) ET18
WRITE(K0,429) ET20
WRITE(K0,1429) ET7
419 FORMAT('      COOLANT TEMPERATURE - STATION 1 ',3(' '), 'ET1 ',
1  G12.6, ' DEG R',10X, 'TA1 + 20. ')
420 FORMAT('      COOLANT TEMPERATURE - STATION 2 ',3(' '), 'ET2 ',
1  G12.6, ' DEG R',10X, 'TA1 + 20. ')
421 FORMAT('      COOLANT TEMPERATURE - STATION 3 ',3(' '), 'ET3 ',
1  G12.6, ' DEG R',10X, 'TA1 + 40. ')
422 FORMAT('      COOLANT TEMPERATURE - STATION 4 ',3(' '), 'ET4 ',
1  G12.6, ' DEG R',10X, 'TA1 + 55. ')
423 FORMAT('      COOLANT TEMPERATURE - STATION 6 ',3(' '), 'ET6 ',
1  G12.6, ' DEG R',10X, 'TA1 + 30. ')
1429 FORMAT('      COOLANT TEMPERATURE - STATION 7 ',3(' '), 'ET7 ',
1  G12.6, ' DEG R',10X, 'TA1 + 20. ')
424 FORMAT('      COOLANT TEMPERATURE - STATION 8 ',3(' '), 'ET8 ',
1  G12.6, ' DEG R',10X, 'TA1 + 65. ')
425 FORMAT('      COOLANT TEMPERATURE - STATION 10 ',3(' '), 'ET10 ',
1  G12.6, ' DEG R',10X, 'TA1 + 65. ')
426 FORMAT('      COOLANT TEMPERATURE - STATION 14 ',3(' '), 'ET14 ',
1  G12.6, ' DEG R',10X, 'TA1 + 30. ')
427 FORMAT('      COOLANT TEMPERATURE - STATION 16 ',3(' '), 'ET16 ',
1  G12.6, ' DEG R',10X, 'TA1 + 75. ')
428 FORMAT('      COOLANT TEMPERATURE - STATION 18 ',3(' '), 'ET18 ',
1  G12.6, ' DEG R',10X, 'TA1 + 65. ')
429 FORMAT('      COOLANT TEMPERATURE - STATION 20 ',3(' '), 'ET20 ',
1  G12.6, ' DEG R',10X, 'TA1 + 65. ')
WRITE(K0,430) ETA2
430 FORMAT('      AIR TEMPERATURE AFTER RADIATOR ',4(' '), 'ETA2 ',
1  G12.6, ' DEG R',10X, 'TA1 + 30. ')
WRITE(K0,431) EBPR
431 FORMAT('      BLOWER PRESSURE RATIO ',9(' '), 'EBPR ',G12.6,
1  ' ',14X, '1.17 ')
WRITE(K0,402) EVIM
402 FORMAT('      INLET VELOCITY ',12(' '), 'EVIM ',G12.6, ' M/SEC',
1  10X, '120. ')
WRITE(K0,432)
432 FORMAT('COOLING SYSTEM FLOWS')
WRITE(K0,433) WI
433 FORMAT('      HEAT EXCHANGER 1 (LIQUID) ',7(' '), 'WI ',
1  G12.6, ' LB/SEC')

```



```

WRITE(KO,434) WII
434 FORMAT('      HEAT EXCHANGER 2 (LIQUID) ',7(' '), 'WII ',
1 G12.6,' LB/SEC')
WRITE(KO,1000) WIII
1000 FORMAT('      HEAT EXCHANGER 3 (LIQUID) ',7(' '), 'WIII ',
1 G12.6,' LB/SEC')
WRITE(KO,435) WB
435 FORMAT('      MIRROR BYPASS ',13(' '), 'WB ',
1 G12.6,' LB/SEC')
WRITE(KO,436) WM
436 FORMAT('      MIRROR ',16(' '), 'WM ',
1 G12.6,' LB/SEC')
WRITE(KO,437) WV1
437 FORMAT('      VACUUM PUMP 1 ',13(' '), 'WV1 ',
1 G12.6,' LB/SEC')
WRITE(KO,438) WV2
438 FORMAT('      VACUUM PUMP 2 ',13(' '), 'WV2 ',
1 G12.6,' LB/SEC')
WRITE(KO,439) WE
439 FORMAT('      E-BEAM ',16(' '), 'WE ',
1 G12.6,' LB/SEC')
WRITE(KO,440) WS
440 FORMAT('      SUSTAINER ',15(' '), 'WS ',
1 G12.6,' LB/SEC')
WRITE(KO,441) CWA
441 FORMAT('      CORRECTED FAN FLOW (AIR) ',7(' '), 'CWA ',
1 G12.6,' CFM')
WRITE(KO,445)
445 FORMAT('0SPECIFICATIONS OF BLOWERS')
WRITE(KO,442) ATAP
442 FORMAT('      BLOWER POLYTROPIC EFFICIENCY ',5(' '), 'ATAP ',
1 G12.6,' -')
WRITE(KO,446) BRPM
446 FORMAT('      BLOWER SPEED ',13(' '), 'BRPM ',G12.6,' RPM')
WRITE(KO,447) NBS
447 FORMAT('      NUMBER OF BLOWER SETS ',9(' '), 'NBS ',16,6X,
1 ' -')
WRITE(KO,448) NBPS
448 FORMAT('      NUMBER OF BLOWERS PER SET ',7(' '), 'NBPS ',
1 16,6X,' -')
WRITE(KO,543) VLM
543 FORMAT('      INLET VELOCITY TOLERANCE ',7(' '), 'VLM ',
1 G12.6,' M/SEC')
WRITE(KO,444)
444 FORMAT('0TUNNEL AREAS')
WRITE(KO,443) A
443 FORMAT('      STATION 1 TO STATION 11 ',8(' '), 'A ',
1 6(1X,G12.3 )/50X,5(1X,G12.3 ),'FT**2')
WRITE(KO,100)
WRITE(KO,101) TITLE
WRITE(KO,500)
500 FORMAT('0 INPUT LIST (CONT.)')
WRITE(KO,501)
501 FORMAT('0HEAT EXCHANGER SPECIFICATIONS',22X,'EXCH 1',4X
1 'EXCH 2',4X, 'EXCH 3',6X, 'RAD', 3X,'UNITS')
WRITE(KO,502)

```

```

502 FORMAT(9X,'DESCRIPTION',25X,'NAME',5X,'(1)', 6X,'(2)', 6X,'(3)',
1 7X,'(4)')
WRITE(KO,503) DL
503 FORMAT('      CORE LENGTH (GAS) ',11(' '), 'DL ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,504) DH
504 FORMAT('      CORE HEIGHT ',14(' '), 'DH ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,505) DW
505 FORMAT('      CORE WIDTH (LIQUID) ',10(' '), 'DW ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,506) DDHG
506 FORMAT('      HYDRAULIC DIAMETER (GAS) ',7(' '), 'DDHG ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,507) DALG
507 FORMAT('      SURFACE AREA / VOLUME (GAS) ',5(' '), 'DALG ',
1 4(2X,G12.3,2X),'1/FT')
WRITE(KO,508) DAFOA
508 FORMAT('      FIN AREA / SURFACE AREA (GAS) ',5(' '), 'DAFOA',
1 4(2X,G12.3,2X),'-')
WRITE(KO,509) DSIG
509 FORMAT('      FREE FLOW AREA / FACE AREA (GAS) ',3(' '), 'DSIG ',
1 4(2X,G12.3,2X),'-')
WRITE(KO,510) DDEL
510 FORMAT('      FIN THICKNESS (GAS) ',10(' '), 'DDEL ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,511) DSL
511 FORMAT('      FIN LENGTH (GAS) ',11(' '), 'DSL ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,516) DDH
516 FORMAT('      HYDRAULIC DIAMETER (LIQUID) ',6(' '), 'DDH ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,514) DALF
514 FORMAT('      SURFACE AREA / VOLUME (LIQUID) ',4(' '), 'DALF ',
1 4(2X,G12.3,2X),'1/FT')
WRITE(KO,550) DAFAL
550 FORMAT('      FIN AREA / SURFACE AREA (LIQUID) ',3(' '), 'DAFAL',
1 4(2X,G12.3,2X),'-')
WRITE(KO,515) DSI
515 FORMAT('      FREE FLOW AREA / FACE AREA (LIQUID) ',2(' '),
1 'DSI ',4(2X,G12.3,2X),'-')
WRITE(KO,512) DA
512 FORMAT('      FIN THICKNESS (LIQUID) ',3(' '), 'DA ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,551) DSLL
551 FORMAT('      FIN LENGTH (LIQUID) ',10(' '), 'DSLL ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,552) AB
552 FORMAT('      PARTING PLATE THICKNESS ',8(' '), 'AP ',
1 4(2X,G12.3,2X),'FT')
WRITE(KO,541) NP
541 FORMAT('      NUMBER OF LIQUID PASSES ',8(' '), 'NP ',
1 4(5X,14,7X),'-')
WRITE(KO,513) DKH

```

```

513 FORMAT('      FIN THERMAL CONDUCTIVITY ',7(' '), 'DKH ',
1 4(2X,G12.6,2X),'BTU/HR-FT-DEG R')
WRITE(KO,517)
517 FORMAT('OHEAT INPUT RATES',39X,'VALUE      UNITS')
WRITE(KO,518) QP
518 FORMAT('      PUMP ',17(' '), 'QP ',
1 2X,G12.6,2X,'BTU/SEC')
WRITE(KO,519) QCM
519 FORMAT('      MIRROR CONTROL ',12(' '), 'GCM ',
1 2X,G12.6,2X,'BTU/SEC')
WRITE(KO,520) QM
520 FORMAT('      MIRROR ',16(' '), 'QM ',
1 2X,G12.6,2X,'BTU/SEC')
WRITE(KO,521) QV1
521 FORMAT('      VACUUM PUMP 1 ',13(' '), 'QV1 ',
1 2X,G12.6,2X,'BTU/SEC')
WRITE(KO,522) QV2
522 FORMAT('      VACUUM PUMP 2 ',13(' '), 'QV2 ',
1 2X,G12.6,2X,'BTU/SEC')
WRITE(KO,523) QE
523 FORMAT('      E-BEAM ',16(' '), 'QE ',
1 2X,G12.6,2X,'BTU/SEC')
WRITE(KO,524) QS
524 FORMAT('      SUSTAINER ',15(' '), 'QS ',
1 2X,G12.6,2X,'BTU/SEC')
WRITE(KO,525)
525 FORMAT('ODIFFUSER LOSS COEFFICIENTS')
WRITE(KO,526) CF23
WRITE(KO,527) CF34
526 FORMAT('      STATION 2  TO  STATION 3 ',7(' '), 'CF23 ',
1 2X,G12.6,2X,'-')
WRITE(KO,544) CF111
WRITE(KO,531) CF910
WRITE(KO,530) CF89
WRITE(KO,529) CF78
WRITE(KO,528) CF45
527 FORMAT('      STATION 3  TO  STATION 4 ',7(' '), 'CF34 ',
1 2X,G12.6,2X,'-')
528 FORMAT('      STATION 4  TO  STATION 5 ',7(' '), 'CF45 ',
1 2X,G12.6,2X,'-')
529 FORMAT('      STATION 7  TO  STATION 8 ',7(' '), 'CF78 ',
1 2X,G12.6,2X,'-')
530 FORMAT('      STATION 8  TO  STATION 9 ',7(' '), 'CF89 ',
1 2X,G12.6,2X,'-')
531 FORMAT('      STATION 9  TO  STATION 10 ',7(' '), 'CF910',
1 2X,G12.6,2X,'-')
544 FORMAT('      STATION 11 TO  STATION 1 ',7(' '), 'CF111',
1 2X,G12.6,2X,'-')
WRITE(KO,532)
532 FORMAT('GAMBIENT CONDITIONS, DECISION VARIABLES, AND CONVERGENCE',
1 ' TOLERANCES')

```

```

WRITE(KO,533) TA1F
533 FORMAT('      AMBIENT TEMPERATURE ',10(' ', '),'TA1F ',2X,G12.6,2X,
1 'DEG F')
WRITE(KO,534) PAT
534 FORMAT('      AMBIENT PRESSURE ',11(' ', '),'PAT ',2X,G12.6,2X,
1 'PSIA')
WRITE(KO,535) RHP
535 FORMAT('      RELATIVE HUMIDITY ',11(' ', '),'RHP ',2X,G12.6,2X,
1 'PERCENT')
WRITE(KO,542) FG
542 FORMAT('      FRACTION OF GLYCOL IN COOLING LIQUID . FG ',
1 G12.6, ' -')
WRITE(KO,536) NLIM
536 FORMAT('      MAXIMUM NUMBER OF LOOP CYCLES ',5(' ', '),'NLIM ',
1 5X,13,8X,'-')
WRITE(KO,537) PLIM
537 FORMAT('      PRESSURE TOLERANCE ',10(' ', '),'PLIM ',2X,G12.6,2X,
1 'PSIA')
WRITE(KO,538) DELM
538 FORMAT('      MACH NUMBER TOLERANCE ',9(' ', '),'DELM ',2X,G12.6,2X,
1 '-')
WRITE(KO,539) ROLIM
539 FORMAT('      DENSITY TOLERANCE ',11(' ', '),'ROLIM',2X,G12.6,2X,
1 'LB/FT**3')
WRITE(KO,540) CONV
540 FORMAT('      STATE VARIABLE TOLERANCES ',7(' ', '),'CONV ',
1 5(2X,G12.3,1X),2(/50X,5(2X,G12.3,1X))/50X,2X,G12.3,2X,
2 'DEG R')
WRITE(KO,100)
100 FORMAT('1')
WRITE(KO,101) TITLE
101 FORMAT(21X,14A6)
CALL GASP(T1G, FN, GAM1G, Z, Z, Z, GMU)
CALL GASP(T2G, FN, GAM2G, Z, Z, Z, GMU)
CALL GASP(T3G, FN, GAM3G, Z, Z, Z, GMU)
CALL GASP(T4G, FN, GAM4G, Z, Z, Z, GMU)
CALL GASP(T5G, FN, GAM5G, Z, Z, Z, GMU)
CALL GASP(T6G, FN, GAM6G, Z, Z, Z, GMU)
CALL GASP(T7G, FN, GAM7G, Z, Z, Z, GMU)
CALL GASP(T8G, FN, GAM8G, Z, Z, Z, GMU)
CALL GASP(T9G, FN, GAM9G, Z, Z, Z, GMU)
CALL GASP(T10G, FN, GAM10G, Z, Z, Z, GMU)
CALL GASP(T11G, FN, GAM11G, Z, Z, Z, GMU)
CON=32.174*1545.43/GMU
VG(1)=FM1*DSQRT(GAM1G*CON*T1G)
VG(2)=FM2*DSQRT(GAM2G*CON*T2G)
VG(3)=FM3*DSQRT(GAM3G*CON*T3G)
VG(4)=FM4*DSQRT(GAM4G*CON*T4G)
VG(5)=FM5*DSQRT(GAM5G*CON*T5G)
VG(6)=FM6*DSQRT(GAM6G*CON*T6G)
VG(7)=FM7*DSQRT(GAM7G*CON*T7G)
VG(8)=FM8*DSQRT(GAM8G*CON*T8G)
VG(9)=FM9*DSQRT(GAM9G*CON*T9G)
VG(10)=FM10*DSQRT(GAM10G*CON*T10G)
VG(11)=FM11*DSQRT(GAM11G*CON*T11G)
DO 28 K=1,11
28 QG(K)=VG(K)*A(K)*60.

```



```

WRITE(KO,102) ALT
102 FORMAT('0 ALTITUDE ',20(' '),1X,G12.6,' (K FT)')
WRITE(KO,103) PAT
103 FORMAT(' AMBIENT PRESSURE ',16(' '),1X,G12.6,' (PSIA)')
WRITE(KO,104) TAIF
104 FORMAT(' AMBIENT TEMPERATURE ',15(' '),1X,G12.6,' (DEG F)')
WRITE(KO,105) RHP
105 FORMAT(' RELATIVE HUMIDITY ',16(' '),1X,G12.6,' (PERCENT)')
WRITE(KO,107) PIGA
107 FORMAT(' LASER INLET PRESSURE ',14(' '),1X,G12.6,' (ATM)')
TIGM=TIG/1.8
WRITE(KO,108) TIGM
108 FORMAT(' LASER INLET TEMPERATURE ',13(' '),1X,G12.6,' (DEG K)')
Z=(T02G-T01G)/1.8
WRITE(KO,142) Z
142 FORMAT(' TEMPERATURE RISE ACROSS CAVITY ',9(' '),1X,G12.6,
1 ' (DEG K)')
WRITE(KO,109) VIM
109 FORMAT(' LASER INLET VELOCITY ',14(' '),1X,G12.6,' (M/SEC)')
WRITE(KO,110) PLKW
110 FORMAT(' LASER OUTPUT POWER . . ',13(' '),1X,G12.6,' (KW)')
WRITE(KO,141) EFFLP
141 FORMAT(' LASER EFFICIENCY ',16(' '),1X,G12.6,' (PERCENT)')
WRITE(KO,114) WG
114 FORMAT(' LASER GAS MASS FLOW RATE ',12(' '),1X,G12.6,
1 ' (LB/SEC)')
WRITE(KO,115) G6G
115 FORMAT(' VOLUME FLOW RATE AT BLOWER INLET ',8(' '),1X,G12.6,
1 ' (CFM)')
WRITE(KO,116) G6CORR
116 FORMAT(' CORRECTED VOLUME FLOW RATE AT BLOWER INLET ',3(' '),
1 1X,G12.6,' (CFM)')
WRITE(KO,139) WA
139 FORMAT(' COOLING AIR FLOW RATE ',14(' '),1X,G12.6,
1 ' (LB/SEC)')
WRITE(KO,140) CWA
140 FORMAT(' COOLING AIR FLOW RATE ',14(' '),1X,G12.6,
1 ' (CFM)')
WRITE(KO,117) BPR
117 FORMAT(' BLOWER PRESSURE RATIO ',14(' '),1X,G12.6,' (-)')
WRITE(KO,111) BLPRM, BLPR
111 FORMAT(' BLOWER POWER REQUIRED ',14(' '),1X,G12.6,' (KW)',
1 8X,G12.6,1X,' (HP)')
WRITE(KO,112) PPRM, PPR
112 FORMAT(' COOLING PUMP POWER REQUIRED ',11(' '),1X,G12.6,
1 ' (KW)',3X,G12.6,1X,' (HP)')
WRITE(KO,113) PFM, PF
113 FORMAT(' COOLING FAN POWER REQUIRED ',11(' '),1X,G12.6,
1 ' (KW)',8X,G12.6,1X,' (HP)')
WRITE(KO,106) FN
106 FORMAT(' LASER GAS MIXTURE ',15(' '),1X,F5.2,3(' TO',F5.2),2X,
1 ' (HE TO N2 TO CO2 TO CO)')
WRITE(KO,143) GMU
143 FORMAT(' MOLECULAR WEIGHT OF GAS ',12(' '),1X,G12.6,
1 ' (-)')
WRITE(KO,118)

```



```

1  'EXCH 2'.      4X.'EXCH 3'.      4X.'RAD'.      4X.'UNITS')
118 FORMAT('0',3X,'HEAT EXCHANGER VARIABLES',14X,'EXCH 1',3X,
1  'EXCH 2',3X,      EXCH 3',5X,      RAD',5X,      'UNITS')
WRITE(KO,119) QDI, QDII, QDIII, QDA
119 FORMAT('  HEAT TRANSFER RATE ',11(' '),2X,4(G12.2,3X),
1  ' BTU/HR')
WRITE(KO,120) DPI, DPII, DPIII, DP
120 FORMAT('  LIQUID PRESSURE DROP ',10(' '),2X,4(G12.2,3X),
1  ' PSIA')
WRITE(KO,121) NP
121 FORMAT('  NUMBER OF LIQUID PASSES ',9(' '),2X,4(3X,12,2X),' -')
NFULL=0
IF (NFULL.NE.0) RETURN
WRITE(KO,122) TMI, TMII, TMIII, TM
122 FORMAT('  MEAN TEMPERATURE ',9(' '),'(LIQUID)',4(' '),2X,
1  4(G12.2,3X),' DEG R')
WRITE(KO,123) TGM1, TGMII, TGM3, TMA
123 FORMAT(32X,'(GAS)',10X,4(G12.2,3X))
WRITE(KO,124) ZIMU, ZIIIMU, Z3MU, ZMU
124 FORMAT('  VISCOSITY ',16(' '),'(LIQUID)',4(' '),2X,4(G12.2,3X),
1  ' LB/FT-SEC')
WRITE(KO,125) GIMU, GIIIMU, G3MU, AMU
WRITE(KO,125) PRI, PRII, PRIII, PR
125 FORMAT('  PRANDTL NUMBER ',11(' '),'(LIQUID)',4(' '),2X,
1  4(G12.2,3X),' -')
WRITE(KO,126) PRGI, PRGII, PRG3, PRA
WRITE(KO,126) CPI, CPII, CPIII, CP
126 FORMAT('  SPECIFIC HEAT ',12(' '),'(LIQUID)',4(' '),2X,
1  4(G12.2,3X),' BTU/LB-DEG R')
WRITE(KO,127) CPGI, CPGII, CPG3, CPA
WRITE(KO,127) GI, GII, GIII, G
127 FORMAT('  MASS FLUX ',16(' '),'(LIQUID)',4(' '),2X,
1  4(G12.2,3X),' LB/FT**2-SEC')
WRITE(KO,128) GGI, GGII, GGIII, GA
WRITE(KO,128) REI, REII, REIII, RE
128 FORMAT('  REYNOLDS NUMBER ',10(' '),'(LIQUID)',4(' '),2X,
1  4(G12.2,3X),' -')
WRITE(KO,129) REGI, REGII, REG3, REA
WRITE(KO,129) FI, FII, FIII, F
129 FORMAT('  FRICTION FACTOR ',10(' '),'(LIQUID)',4(' '),2X,
1  4(G12.2,3X),' -')
WRITE(KO,130) GFI, GFII, GFIII, AF
WRITE(KO,130) ZJI, ZJII, ZJIII, ZJ
130 FORMAT('  HEAT TRANSFER FACTOR ',5(' '),'(LIQUID)',4(' '),2X,
1  4(G12.2,3X),' -')
WRITE(KO,131) GJI, GJII, GJIII, AJ
WRITE(KO,131) HI, HII, HIII, H
131 FORMAT('  HEAT TRANSFER COEF. ',6(' '),'(LIQUID)',4(' '),2X,
1  4(G12.2,3X),' BTU/FT**2-SEC-DEG R')
WRITE(KO,132) HGI, HGII, HGIII, HA
WRITE(KO,132) CI, CII, CIII, C
132 FORMAT('  FLUID CAPACITY RATE ',6(' '),'(LIQUID)',4(' '),2X,

```

```

1  4(G12.2,3X),' BTU/SEC-DEG R')
  WRITE(KO,123) CGI, CGII, CGIII, CA
  WRITE(KO,133) UI, UII, UIII, U
133 FORMAT(' OVERALL HEAT TRANSFER COEF. ',7(' '),2X,4(G12.2,3X),
1  ' BTU/FT**2-SEC-DEG R')
  WRITE(KO,134) AGI, AGII, AGIII, AA
134 FORMAT(' GAS HEAT TRANSFER SURFACE AREA ',5(' '),2X,
1  4(G12.2,3X),' FT**2')
  WRITE(KO,135) TUNI, TUNII, TUN3, TUN
135 FORMAT(' NUMBER OF TRANSFER UNITS ',8(' '),2X,
1  4(G12.2,3X),' -')
  WRITE(KO,136) TOWI, TOWII, TOW3, TOW
136 FORMAT(' CAP GAMMA ',16(' '),2X,4(G12.2,3X),' -')
  WRITE(KO,137) ESSI, ESSII, ESS3, ESS
137 FORMAT(' SINGLE PASS EFFECTIVENESS ',8(' '),2X,
1  4(G12.2,3X),' -')
  WRITE(KO,138) EPSI, EPSII, EPS3, EPSA
138 FORMAT(' TOTAL EFFECTIVENESS ',11(' '),2X,
1  4(G12.2,3X),' -')
  WRITE(KO,100)
  WRITE(KO,101) TITLE
  WRITE(KO,200)
200 FORMAT('0',16X,'GAS FLOW SYSTEM VARIABLES BY STATION')
  WRITE(KO,201)
201 FORMAT('0 STATION NUMBER',15X,'1', 8X,'2', 8X,'3', 8X,'4',
1  8X,'5', 8X,'6'/34X,'7', 8X,'8', 8X,'9', 7X,'10', 7X,'11')
  WRITE(KO,204) P01G, P02G, P03G, P04G, P05G, P06G, P07G, P08G,
1  P09G, P010G, P011G
204 FORMAT('0 TOTAL PRESSURE (PSIA)',
1  6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
  WRITE(KO,203) P1G, P2G, P3G, P4G, P5G, P6G, P7G, P8G, P9G, P10G,
1  P11G
203 FORMAT('0 STATIC PRESSURE (PSIA)',
1  6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
  WRITE(KO,206) T01G, T02G, T03G, T04G, T05G, T06G, T07G, T08G,
1  T09G, T010G, T011G
206 FORMAT('0 TOTAL TEMP. (DEG R)',
1  6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
  WRITE(KO,205) T1G, T2G, T3G, T4G, T5G, T6G, T7G, T8G, T9G, T10G,
1  T11G
205 FORMAT('0 STATIC TEMPERATURE (DEG R)',
1  6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
  WRITE(KO,207) FM1, FM2, FM3, FM4, FM5, FM6, FM7, FM8, FM9, FM10,
1  FM11
207 FORMAT('0 MACH NUMBER (-)',
1  6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
  WRITE(KO,208) VG
208 FORMAT('0 VELOCITY (FT/SEC)',
1  6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
  WRITE(KO,209) GG
209 FORMAT('0 VOL. FLOW RATE (CFM)',
1  6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
  Z=GMU*.093178
  ROG( 1)=PIG*Z/T1G
  ROG( 2)=P2G*Z/T2G
  ROG( 3)=P3G*Z/T3G
  ROG( 4)=P4G*Z/T4G

```

```

      ROG(5) = P5G*Z/T5G
      ROG(6)=P6G*Z/T6G
      ROG(7)=P7G*Z/T7G
      ROG(8)=P8G*Z/T8G
      ROG(9) = P9G*Z/T9G
      ROG(10)=P10G*Z/T10G
      ROG(11)=P11G*Z/T11G
      WRITE(K0,220) ROG
220  FORMAT('O      DENSITY      (LB/FT**3)',
1     6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
      WRITE(K0,212) A
212  FORMAT('O      AREA      (FT**2)',
1     6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
      WRITE(K0,213) GAM1G, GAM2G, GAM3G, GAM4G, GAM5G, GAM6G, GAM7G,
1     GAM8G, GAM9G, GAM10G, GAM11G
213  FORMAT('O      GAMMA      (-)',
1     6(1X,G12.3,1X)/31X,5(1X,G12.3,1X))
      PD(1) = (P01G-P02G)*27.7
      PD(2)=(P02G-P03G)*27.7
      PD(3)=(P03G-P04G)*27.7
      PD(4)=(P04G-P05G)*27.7
      PD(5)=(P05G-P06G)*27.7
      PD(6)=(P06G-P07G)*27.7
      PD(7)=(P07G-P08G)*27.7
      PD(8)=(P08G-P09G)*27.7
      PD(9)=(P09G-P010G)*27.7
      PD(10)=(P010G-P011G)*27.7
      PD(11)=(P011G-P01G)*27.7
      DO 27 K=1,11
27  PP(K)=PD(K)/(27.7*P06G)
      WRITE(K0,210) PD
210  FORMAT('O      PRESSURE DROP      (IN H2O)',6X,
1     6(1X,G12.3,1X)/37X,5(1X,G12.3,1X))
      WRITE(K0,211) PP
211  FORMAT('O      PRESSURE DROP / P06      (-)',6X,
1     6(1X,G12.3,1X)/37X,5(1X,G12.3,1X))
      WRITE(K0,214)
214  FORMAT('O',12X,'COOLING AIR VARIABLES')
      WRITE(K0,215)
215  FORMAT('O      STATION NUMBER',18X,'1A',12X,'2A')
      WRITE(K0,216) PAT, PA2
216  FORMAT('O      PRESSURE',12X,'(PSIA)',2(1X,G12.6,1X))
      WRITE(K0,217) TA1, TA2
217  FORMAT('O      TEMPERATURE',8X,'(DEG R)',2(1X,G12.6,1X))
      WRITE(K0,218) ROA1, ROA2
218  FORMAT('O      DENSITY',9X,'(LB/FT**3)',2(1X,G12.6,1X))
      DPPA=(PAT-PA2)*27.7
      WRITE(K0,219) DPPA
219  FORMAT('O      PRESSURE DROP      (IN H2O)',7X,G12.6)
      WRITE(K0,100)
      WRITE(K0,101) TITLE
      WRITE(K0,300)

```

```

300 FORMAT('0',16X,'COOLING SYSTEM VARIABLES BY STATION')
    WRITE(KO,301)
301 FORMAT('0      STATION NUMBER',19X,'1',13X,'2',13X,'3',13X,'4',13X,
1  '5',13X,'6',13X,'7',13X,'8',13X,'9',12X,'10',12X,'11',12X,
2  '12',12X,'13',12X,'14',12X,'15',12X,'16',12X,'17',12X,'18',
3  '19',12X,'20')
    WRITE(KO,302) P
302 FORMAT('0      PRESSURE                (PSIA)',
1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
    WRITE(KO,303) T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T12,
1  T13, T14, T15, T16, T17, T18, T19, T20
303 FORMAT('0      TEMPERATURE            (DEG R)',
1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
    WRITE(KO,304) VC
304 FORMAT('0      VELOCITY                (FT/SEC)',
1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
    WRITE(KO,305) QC
305 FORMAT('0      VOL. FLOW RATE (FT**3/SEC)',
1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
    WRITE(KO,306) GCG
306 FORMAT('0      VOL. FLOW RATE  (GAL/MIN)',
1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
    WRITE(KO,307) DPC
    WRITE(KO,309) AC
309 FORMAT('0      AREA                    (FT**2)',
1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
307 FORMAT('0      PRESSURE DROP            (PSIA)',
1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
    WRITE(KO,308) DPCR
308 FORMAT('0      PRESSURE DROP / P1      (-)',
1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
    RETURN
    END

```



281



AD-A068 547

ALABAMA UNIV IN HUNTSVILLE SCHOOL OF SCIENCE AND ENG--ETC F/6 20/5  
INVESTIGATION OF TRANSIENT FLOW AND HEATING PROBLEMS CHARACTERI--ETC(U)  
MAR 79 C C SHIH, G R KARR, J F PERKINS DAAK40-77-C-0161

UNCLASSIFIED

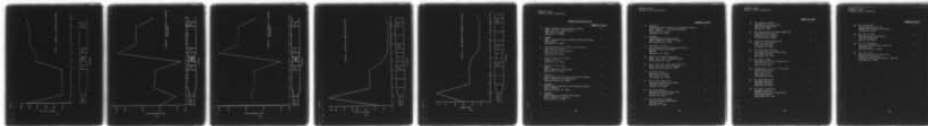
UAH-RR-219

DRCPM-HEL-CR-79-8

NL

4 OF 4

AD  
A068547



END  
DATE  
FILMED  
6-79  
DDC

FN	=	.30000000000000000000+001,	.20000000000000000000+001,
		.50000000000000000000+000,	.50000000000000000000+000,
ACN	=	.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
		.00000000000000000000+000,	.00000000000000000000+000,
DCM	=	.86259999999999999999+001	
DL	=	.20000000000000000000+001,	.20000000000000000000+001,
		.20000000000000000000+001,	.22312500000000000000+001
DH	=	.66666699999999999999+000,	.66666699999999999999+000,
		.66666699999999999999+000,	.19792917000000000000+002
DW	=	.20000000000000000000+001,	.20000000000000000000+001,
		.20000000000000000000+001,	.60416699999999999999+000
DDHG	=	.25500000000000000000-002,	.20200000000000000000-002,
		.20000000000000000000-002,	.78199999999999999999-002
DALG	=	.24460600000000000000+003,	.24460600000000000000+003,
		.24460600000000000000-003,	.33675999999999999999+003
DAFOA	=	.86300000000000000000+000,	.86300000000000000000+000,
		.86300000000000000000+000,	.81000000000000000000+000
DSIG	=	.76989738999999999999+000,	.76939738999999999999+000,
		.76989738999999999999+000,	.65836579999999999999+000
DDLE	=	.49999999999999999999-003,	.49999999999999999999-003,
		.49999999999999999999-003,	.49999999999999999999-003
DA	=	.49999999999999999999-003,	.49999999999999999999-003,
		.49999999999999999999-003,	.49999999999999999999-003
DKH	=	.10000000000000000000+003,	.10000000000000000000+003,
		.10000000000000000000+003,	.10000000000000000000+003
DSL	=	.22650000000000000000-001,	.22650000000000000000-001,
		.22650000000000000000-001,	.10458300000000000000-001
DSI	=	.72719999999999999999-001,	.72717999999999999999-001,
		.72717999999999999999-001,	.13328000000000000000+000
DALF	=	.72717999999999999999+002,	.72717999999999999999+002,
		.72717999999999999999+002,	.13328000000000000000+003
DDH	=	.99999999999999999999-003,	.99999999999999999999-003,
		.99999999999999999999-003,	.39999999999999999999-002
NP	=	+1,	+1,
PAT	=	.14690000000000000000+002	
RHP	=	.10000000000000000000+003	
ESPR	=	.00000000000000000000+000	
A	=	.2152992170000660520+000,	.00000000000000000000+000,
		.54539999999999999999+000,	.54539999999999999999+000,
		.54539999999999999999+000,	.34910000000000000000+000,
		.54539999999999999999+000,	.54539999999999999999+000,
		.54539999999999999999+000,	.54539999999999999999+000,
		.43055641600000000000+000	

NLIM	=	+30	
ROLIM	=	.999999999999999970-003	
PLIM	=	.999999999999999970-003	
FG	=	.000000000000000000+000	
BRPM	=	.112000000000000000+005	
VLIM	=	.500000000000000000+000	
NBS	=	+7	
NBPS	=	+2	
JCPRO	=	-1	
RO1	=	.415000000000000000-002	
DAFAL	=	.507999999999999990+000,	.507999999999999990+000,
		.507999999999999990+000,	.507999999999999990+000
DSLL	=	.211667000000000000-002,	.211667000000000000-002,
		.211667000000000000-002,	.211667000000000000-002
AB	=	.208330000000000000-002,	.208330000000000000-002,
		.208330000000000000-002,	.208330000000000000-002
CONV	=	.500000000000000000+000,	.500000000000000000+000,
		.500000000000000000+000,	.500000000000000000+000,
		.500000000000000000+000,	.500000000000000000+000,
		.500000000000000000+000,	.500000000000000000+000,
		.500000000000000000+000,	.500000000000000000+000,
		.500000000000000000+000,	.500000000000000000+000,
		.500000000000000000+000,	.500000000000000000+000,
		.500000000000000000+000,	.500000000000000000+000,
		.500000000000000000+000,	.500000000000000000+000
DELM	=	.999999999999999970-003	
NDSSN	=	+2	
NCS	=	+1	

# INPUT LIST CAVITY \* LASER SPECIFICATIONS

DESCRIPTION	NAME	VALUE	UNITS
INLET PRESSURE	PIGA	.500000+000	ATM
INLET HEIGHT	H1M	.500000+001	CM
WIDTH IN FLOW DIRECTION	WT1M	.500000+001	CM
LENGTH	CL1M	.400000+002	CM
INLET HYDRAULIC DIAMETER	DCM	.862800+001	CM
LASER OUTPUT POWER	PLKW	.500000+002	KW
LASER EFFICIENCY	EFFLP	.100000+002	PERCENT
DESIGN OPTION	NDSGN	?	-
GAS MIXTURE	FN	3.00 2.00 .50 .50	HE TO N2 TO CO2 TO CO

INITIAL ESTIMATE OF STEADY STATE QUANTITIES	NAME	VALUE	UNITS	IF = 0., USES
GAS STATIC TEMPERATURE - STATION 1	ET1G	.000000	DEG R	TA1 + 20.
GAS TOTAL TEMPERATURE - STATION 2	ET02G	.000000	DEG R	TA1 + 210.
GAS TOTAL TEMPERATURE - STATION 6	ET06G	.000000	DEG R	TA1 + 30.
GAS TOTAL TEMPERATURE - STATION 7	ET07G	.000000	DEG R	TA1 + 70.
COOLANT TEMPERATURE - STATION 1	ET1	.000000	DEG R	TA1 + 20.
COOLANT TEMPERATURE - STATION 2	ET2	.000000	DEG R	TA1 + 20.
COOLANT TEMPERATURE - STATION 3	ET3	.000000	DEG R	TA1 + 40.
COOLANT TEMPERATURE - STATION 4	ET4	.000000	DEG R	TA1 + 55.
COOLANT TEMPERATURE - STATION 6	ET6	.000000	DEG R	TA1 + 30.
COOLANT TEMPERATURE - STATION 8	ET8	.000000	DEG R	TA1 + 65.
COOLANT TEMPERATURE - STATION 10	ET10	.000000	DEG R	TA1 + 65.
COOLANT TEMPERATURE - STATION 14	ET14	.000000	DEG R	TA1 + 30.
COOLANT TEMPERATURE - STATION 16	ET16	.000000	DEG R	TA1 + 75.
COOLANT TEMPERATURE - STATION 18	ET18	.000000	DEG R	TA1 + 65.
COOLANT TEMPERATURE - STATION 20	ET20	.000000	DEG R	TA1 + 65.
COOLANT TEMPERATURE - STATION 7	ET7	.000000	DEG R	TA1 + 20.
AIR TEMPERATURE AFTER RADIATOR	ETA2	.000000	DEG R	TA1 + 30.
BLOWER PRESSURE RATIO	FLPR	.000000	-	1.17
INLET VELOCITY	LVIM	.250000+002	M/SEC	120.

# COOLING SYSTEM FLOWS

HEAT EXCHANGER 1 (LIQUID)	. . . . .	WI	.917400+000	LB/SEC
HEAT EXCHANGER 2 (LIQUID)	. . . . .	WII	.917400+000	LB/SEC
HEAT EXCHANGER 3 (LIQUID)	. . . . .	WIII	.917400+000	LB/SEC
MIRROR BYPASS	. . . . .	WB	.500000+000	LB/SEC
MIRROR	. . . . .	WM	.908000+000	LB/SEC
VACUUM PUMP 1	. . . . .	WV1	.910000-001	LB/SEC
VACUUM PUMP 2	. . . . .	WV2	.318000+000	LB/SEC
E-BEAM	. . . . .	WE	.908000+000	LB/SEC
SUSTAINER	. . . . .	WS	.455000+001	LB/SEC
CORRECTED FAN FLOW (AIR)	. . . . .	CWA	.500000+006	CFM

# SPECIFICATIONS OF BLOWERS

BLOWER POLYTROPIC EFFICIENCY	. . . . .	ATAB	.700000+000	-
BLOWER SPEED	. . . . .	BRPM	.112000+005	RPM
NUMBER OF BLOWER SETS	. . . . .	NBS	7	-
NUMBER OF BLOWERS PER SET	. . . . .	NEPS	2	-
INLET VELOCITY TOLERANCE	. . . . .	VLIM	.500000+000	M/SEC

# TUNNEL AREAS

STATION 1 TO STATION 11	. . . . .	A	.215+000	.215+000	.545+000	.545+000	.349+000
			.545+000	.545+000	.545+000	.545+000	.431+000FT*2



# INPUT LIST (CONT.)

## HEAT EXCHANGER SPECIFICATIONS

DESCRIPTION	EXCH 1 (1)	EXCH 2 (2)	EXCH 3 (3)	KAD (4)	UNITS
CORE LENGTH (GAS)	.200+001	.200+001	.200+001	.228+001	FT
CORE HEIGHT	.667+000	.667+000	.667+000	.198+002	FT
CORE WIDTH (LIQUID)	.200+001	.200+001	.200+001	.200+001	FT
HYDRAULIC DIAMETER (GAS)	.255-002	.202-002	.200-002	.762-002	FT
SURFACE AREA / VOLUME (GAS)	.245+003	.245+003	.245+003	.245+003	1/FT
FIN AREA / SURFACE AREA (GAS)	.863+000	.863+000	.863+000	.810+000	-
FREE FLOW AREA / FACE AREA (GAS)	.770+000	.770+000	.770+000	.658+000	-
FIN THICKNESS (GAS)	.500-003	.500-003	.500-003	.500-003	FT
FIN LENGTH (GAS)	.226-001	.226-001	.226-001	.105-001	FT
HYDRAULIC DIAMETER (LIQUID)	.100-002	.100-002	.100-002	.400-002	FT
SURFACE AREA / VOLUME (LIQUID)	.727+002	.727+002	.727+002	.133+003	1/FT
FIN AREA / SURFACE AREA (LIQUID)	.508+000	.508+000	.508+000	.508+000	-
FREE FLOW AREA / FACE AREA (LIQUID)	.727-001	.727-001	.727-001	.133+000	-
FIN THICKNESS (LIQUID)	.500-003	.500-003	.500-003	.500-003	FT
FIN LENGTH (LIQUID)	.212-002	.212-002	.212-002	.212-002	FT
PARTING PLATE THICKNESS	.208-002	.208-002	.208-002	.208-002	FT
NUMBER OF LIQUID PASSES	1	1	1	4	-
FIN THERMAL CONDUCTIVITY	.100000+003	.100000+003	.100000+003	.100000+003	BTU/ HR-FT

## HEAT INPUT RATES

	VALUE	UNITS
PUMP	.350000+001	BTU/SEC
MIRROR CONTROL	.950000+000	BTU/SEC
MIRROR	.473000+001	BTU/SEC
VACUUM PUMP 1	.473000+000	BTU/SEC
VACUUM PUMP 2	.426000+001	BTU/SEC
U-BEAM	.473000+001	BTU/SEC
SUSTAINER	.000000	BTU/SEC

## DIFFUSER LOSS COEFFICIENTS

STATION 2 TO STATION 3	CF23 .800000-001	-
STATION 3 TO STATION 4	CF34 .150000+000	-
STATION 11 TO STATION 1	CF111.150000+000	-
STATION 9 TO STATION 10	CF910.300000-001	-
STATION 8 TO STATION 9	CF89 .150000+000	-
STATION 7 TO STATION 8	CF78 .150000+000	-
STATION 4 TO STATION 5	CF45 .300000-001	-

AMBIENT CONDITIONS, DECISION VARIABLES, AND CONVERGENCE TOLERANCES  
 AMBIENT TEMPERATURE . . . . . TA1F -.50000+002 DEG F  
 AMBIENT PRESSURE . . . . . PAT .146900+002 PSIA  
 RELATIVE HUMIDITY . . . . . RHP .100000+003 PERCENT  
 FRACTION OF GLYCOL IN COOLING LIQUID . . . . . FG .000000 -  
 MAXIMUM NUMBER OF LOOP CYCLES . . . . . NLIM 30 -  
 PRESSURE TOLERANCE . . . . . PLIM .100000-002 PSIA  
 MACH NUMBER TOLERANCE . . . . . DELM .100000-002 -  
 DENSITY TOLERANCE . . . . . ROLIM .100000-002 LB/FT\*3  
 STATE VARIABLE TOLERANCES . . . . . CONV .500 .500 .500 .500 .500  
 .500 .500 .500 .500 .500  
 .500 DFG R

# LASER TEST CASE

ALTITUDE . . . . . 000000 (K FT)  
 AMBIENT PRESSURE . . . . . 146900+002 (PSIA)  
 AMBIENT TEMPERATURE . . . . . -500000+002 (DEG F)  
 RELATIVE HUMIDITY . . . . . 100000+003 (PERCENT)  
 LASER INLET PRESSURE . . . . . 500000+000 (ATM)  
 LASER INLET TEMPERATURE . . . . . 27604+007 (DEG K)  
 TEMPERATURE RISE ACROSS CAVITY . . . . . 120208+004 (DEG K)  
 LASER INLET VELOCITY . . . . . 250000+002 (M/SEC)  
 LASER OUTPUT POWER . . . . . 500000+002 (KW)  
 LASER EFFICIENCY . . . . . 100000+002 (PERCENT)  
 LASER GAS MASS FLOW RATE . . . . . 511910+000 (LB/SEC)  
 VOLUME FLOW RATE AT BLOWER INLET . . . . . 114994+004 (CFM)  
 CORRECTED VOLUME FLOW RATE AT BLOWER INLET . . . . . 907787+003 (CFM)  
 COOLING AIR FLOW RATE . . . . . 716645+003 (LB/SEC)  
 COOLING AIR FLOW RATE . . . . . 500000+006 (CFM)  
 BLOWER PRESSURE RATIO . . . . . 100322+001 (-)  
 BLOWER POWER REQUIRED . . . . . 158944+000 (KW)  
 COOLING PUMP POWER REQUIRED . . . . . 000000 (KW)  
 COOLING FAN POWER REQUIRED . . . . . 746457+005 (KW)  
 LASER GAS MIXTURE . . . . . 3.00 TO 2.00 TO .50 TO .50 (HE TO N2 TO CO2 TO CO)  
 MOLECULAR WEIGHT OF GAS . . . . . 173403+002 (-)

.213147+000 (HP)  
 .000000 (HP)  
 .100101+006 (HP)

HEAT EXCHANGER VARIABLES						
	EXCH 1	EXCH 2	EXCH 3	RAD	UNITS	
HEAT TRANSFER RATE	.15+007	.27+006	.27+006	.18+007	BTU/HR	
LIQUID PRESSURE DROP	.00	.00	.00	.00	PSIA	
NUMBER OF LIQUID PASSES	1	1	1	4	-	
MEAN TEMPERATURE	.63+003	.45+003	.41+003	.44+003	DEG R	
	(GAS)	.99+003	.41+003	.43+003		
VISCOSITY	.10-004	.10-004	.10-004	.10-004	LB/FT-SEC	
	(GAS)	.20-004	.10-004	.11-004		
PRANDTL NUMBER	.94+001	.11+000	.12+000	.12+000	-	
	(GAS)	.50+000	.43+000	.72+000		
SPECIFIC HEAT	.10+001	.10+001	.10+001	.10+001	BTU/LB-DEG R	
	(GAS)	.37+000	.35+000	.24+000		
MASS FLUX	.95+001	.95+001	.95+001	.73+001	LB/FT**2-SEC	
	(GAS)	.50+000	.50+000	.24+002		
REYNOLDS NUMBLR	.95+003	.95+003	.95+003	.29+004	-	
	(GAS)	.63+002	.98+002	.18+005		
FRICTION FACTOR	.00	.00	.00	.00	-	
	(GAS)	.50+002	.41-001	.30-001		
HEAT TRANSFER FACTOR	.11-001	.11-001	.11-001	.77-002	-	
	(GAS)	.36-001	.36-001	.55-002		
HEAT TRANSFER COEF.	.49+000	.43+000	.43+000	.24+000	BTU/FT**2-SEC-DEG R	
	(GAS)	.10-001	.11-001	.39-001		
FLUID CAPACITY RATE	.92+000	.92+000	.92+000	.96+001	BTU/SEC-DEG R	
	(GAS)	.19+000	.18+000	.17+003		
OVERALL HEAT TRANSFER COEF.	.81-002	.65-002	.85-002	.30-001	BTU/FT**2-SEC-DEG R	
GAS HEAT TRANSFER SURFACE AREA	.65+003	.65+003	.65+003	.22+005	FT**2	
NUMBER OF TRANSFER UNITS	.28+002	.31+002	.00	.68+002	-	
CAP GAMMA	.10+001	.10+001	.10+001	.61+000	-	
SINGLE PASS EFFECTIVENESS	.99+000	.99+000	.99+000	.10+001	-	
TOTAL EFFECTIVENESS	.99+000	.99+000	.99+000	.10+001	-	

# GAS FLOW SYSTEM VARIABLES BY STATION

STATION NUMBER	1 7	2 8	3 9	4 10	5 11	6
TOTAL PRESSURE (PSIA)	.737+001 .742+001	.741+001 .740+001	.740+001 .740+001	.739+001 .740+001	.739+001 .737+001	.739+001
STATIC PRESSURE (PSIA)	.735+001 .742+001	.727+001 .739+001	.738+001 .739+001	.737+001 .739+001	.737+001 .737+001	.739+001
TOTAL TEMP. (DEG R)	.410+003 .427+003	.257+004 .413+003	.257+004 .413+003	.257+004 .413+003	.257+004 .410+003	.426+003
STATIC TEMPERATURE (DEG R)	.410+003 .427+003	.256+004 .413+003	.257+004 .413+003	.257+004 .413+003	.257+004 .410+003	.426+003
MACH NUMBER (-)	.620-001 .248-001	.164+000 .244-001	.641-001 .244-001	.642-001 .244-001	.642-001 .310-001	.388-001
VELOCITY (FT/SEC)	.820+002 .334+002	.518+003 .324+002	.203+003 .324+002	.203+003 .324+002	.203+003 .410+002	.523+002
VOL. FLOW RATE (CFM)	.106+004 .109+004	.670+004 .106+004	.663+004 .106+004	.663+004 .106+004	.663+004 .106+004	.110+004
DENSITY (LB/FT**3)	.290-001 .281-001	.459-002 .289-001	.463-002 .289-001	.463-002 .289-001	.463-002 .290-001	.280-001
AREA (FT**2)	.215+000 .545+000	.215+000 .545+000	.545+000 .545+000	.545+000 .545+000	.545+000 .431+000	.349+000
GAMMA (-)	.149+001 .149+001	.135+001 .149+001	.135+001 .149+001	.135+001 .149+001	.135+001 .149+001	.149+001
PRESSURE DROP (IN H2O)	-.994+000 .692+000	.297+000 .137-001	.874-001 .273-002	.171-001 .671+000	-.675-001 .218-001	-.741+000
PRESSURE DROP / P06 (-)	-.485-002 .338-002	.145-002 .667-004	.427-003 .133-004	.833-004 .328-002	-.329-003 .106-003	-.362-002



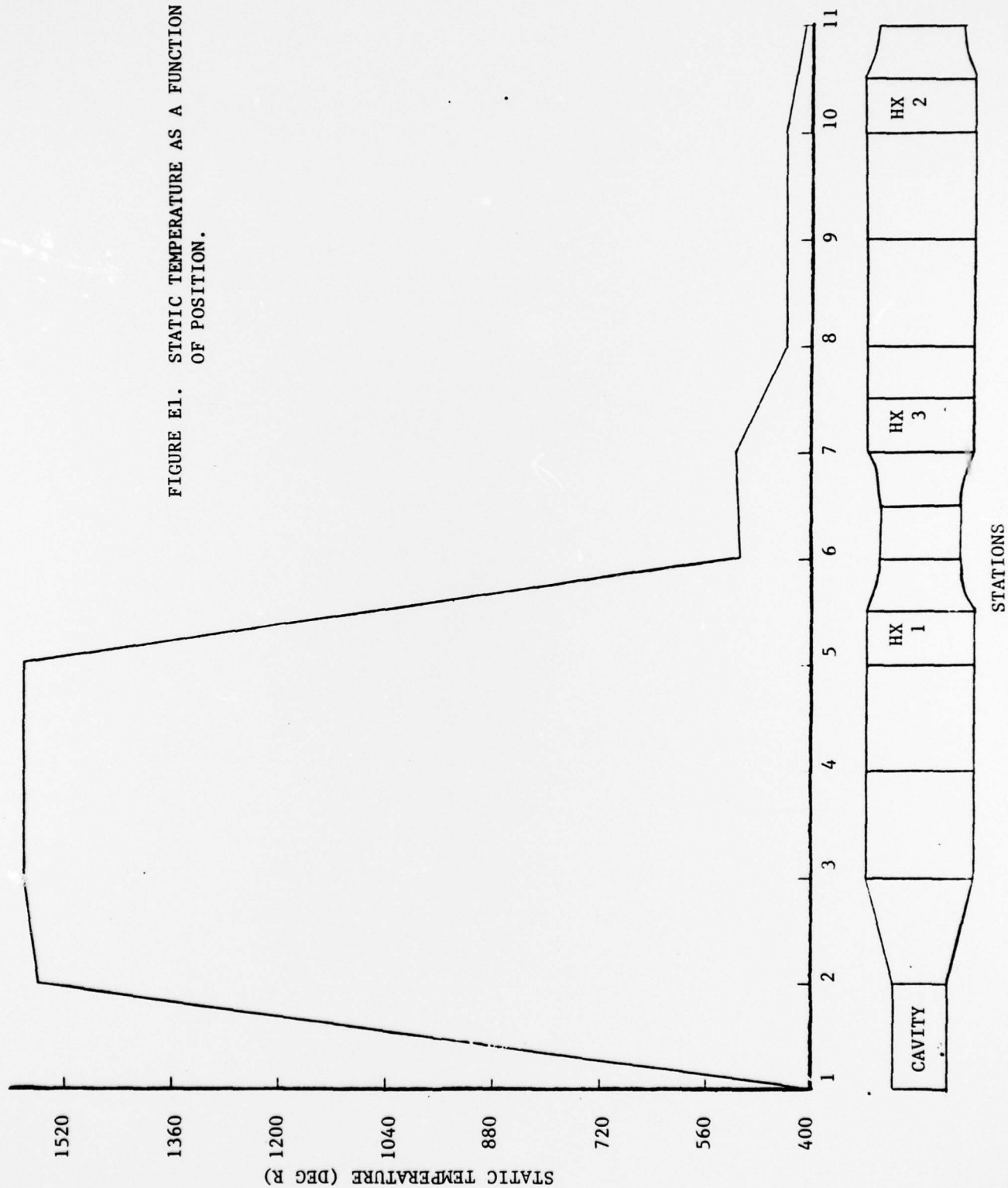
# COOLING AIR VARIABLES

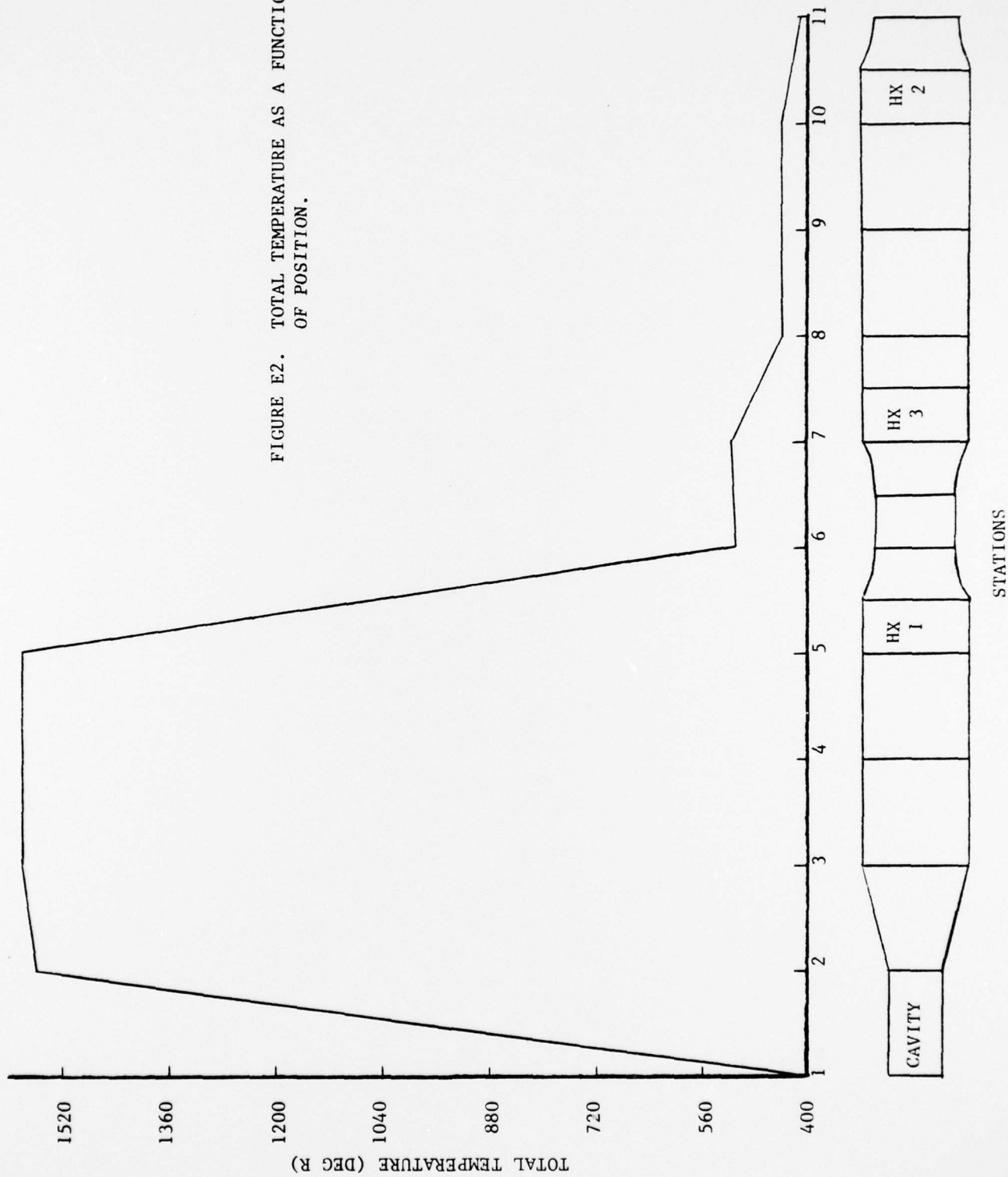
STATION NUMBER		1A	2A
PRESSURE	(PSIA)	.146900+002	-.102425+001
TEMPERATURE	(DEG R)	.409690+003	.412585+003
DENSITY	(LB/FT**3)	.967795-001	-.670055-002
PRESSURE DROP	(IN H2O)	.435285+003	



APPENDIX E

FIGURE E1. STATIC TEMPERATURE AS A FUNCTION OF POSITION.





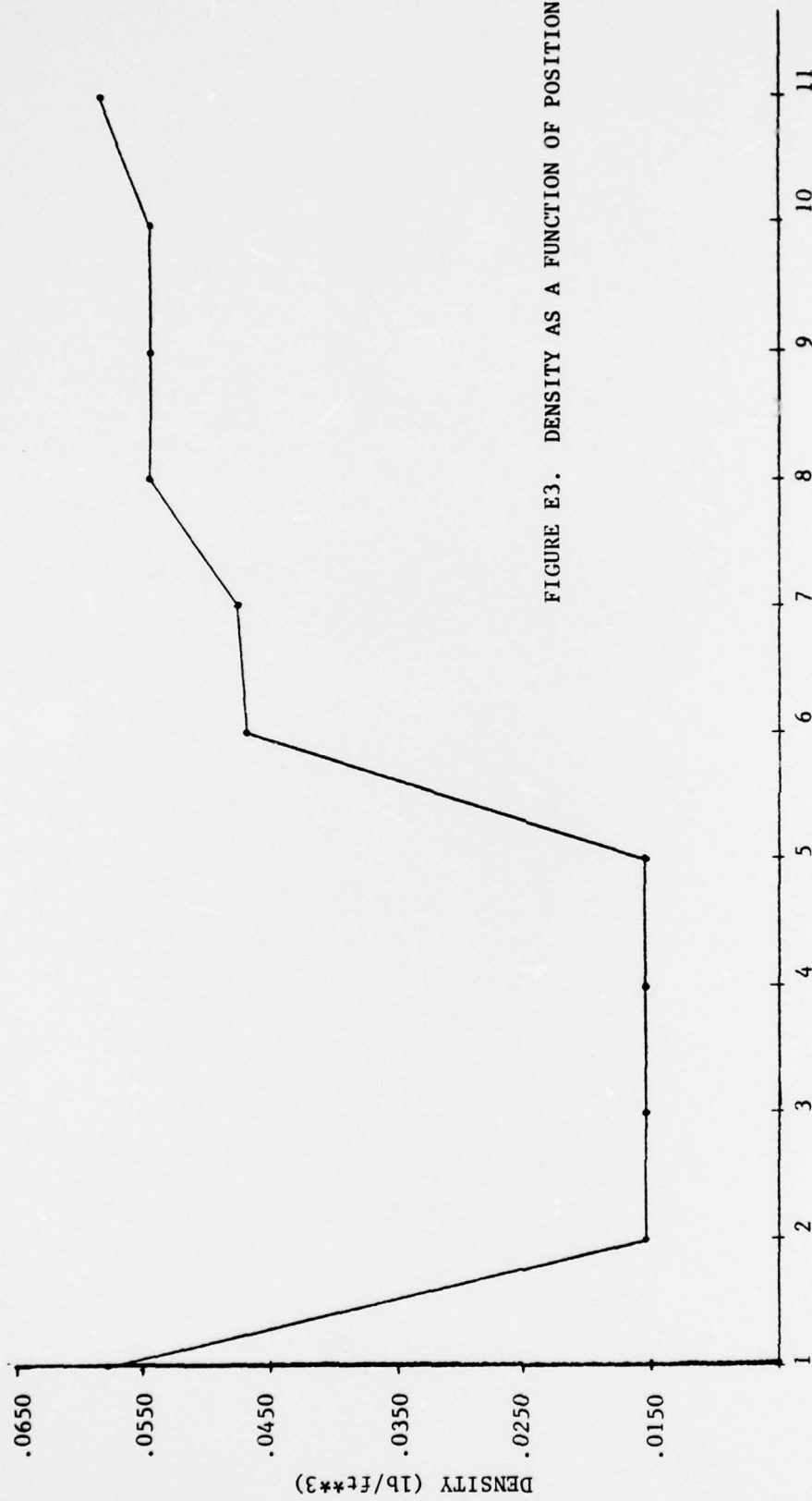
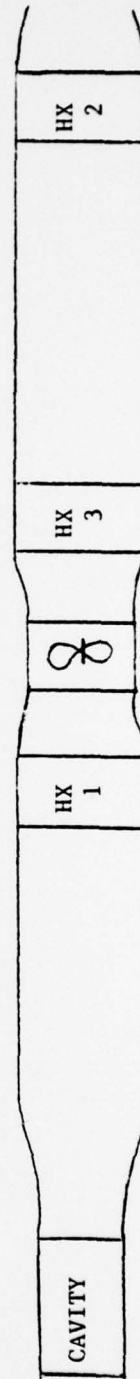


FIGURE E3. DENSITY AS A FUNCTION OF POSITION.



STATIONS

STATIC PRESSURE (PSIA)

295

14.95

14.90

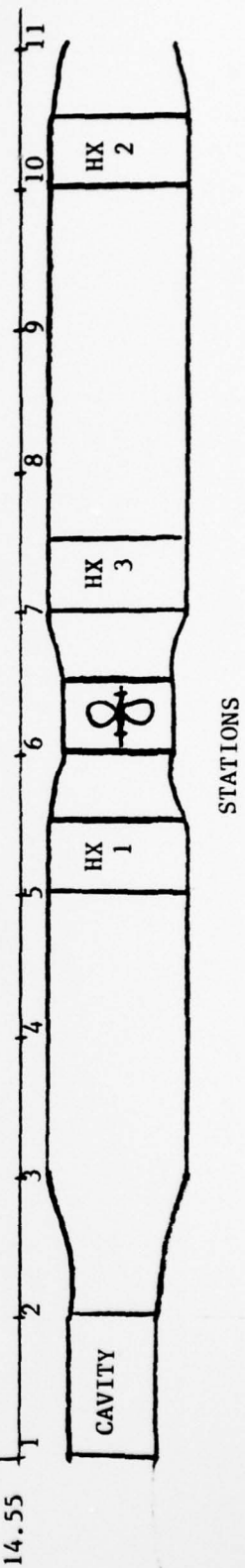
14.80

14.70

14.60

14.55

FIGURE E4. STATIC PRESSURE AS A FUNCTION OF POSITION.





TOTAL PRESSURE (PSIA)

14.95

14.90

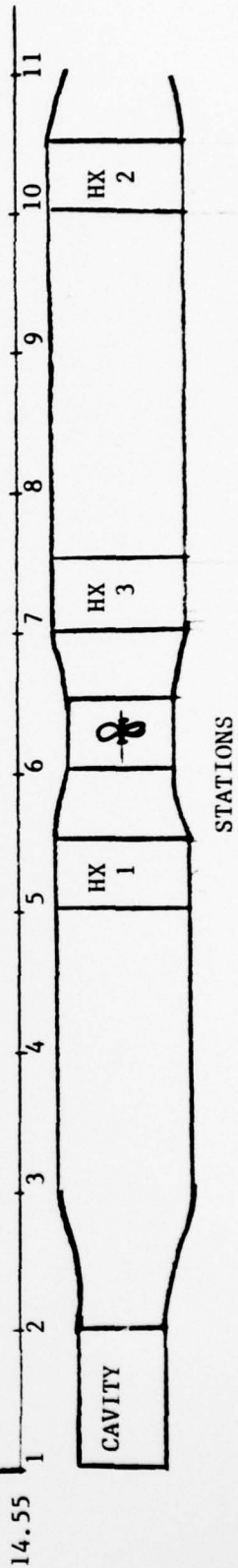
14.80

14.70

14.60

14.55

FIGURE E5. TOTAL PRESSURE AS A FUNCTION OF POSITION.



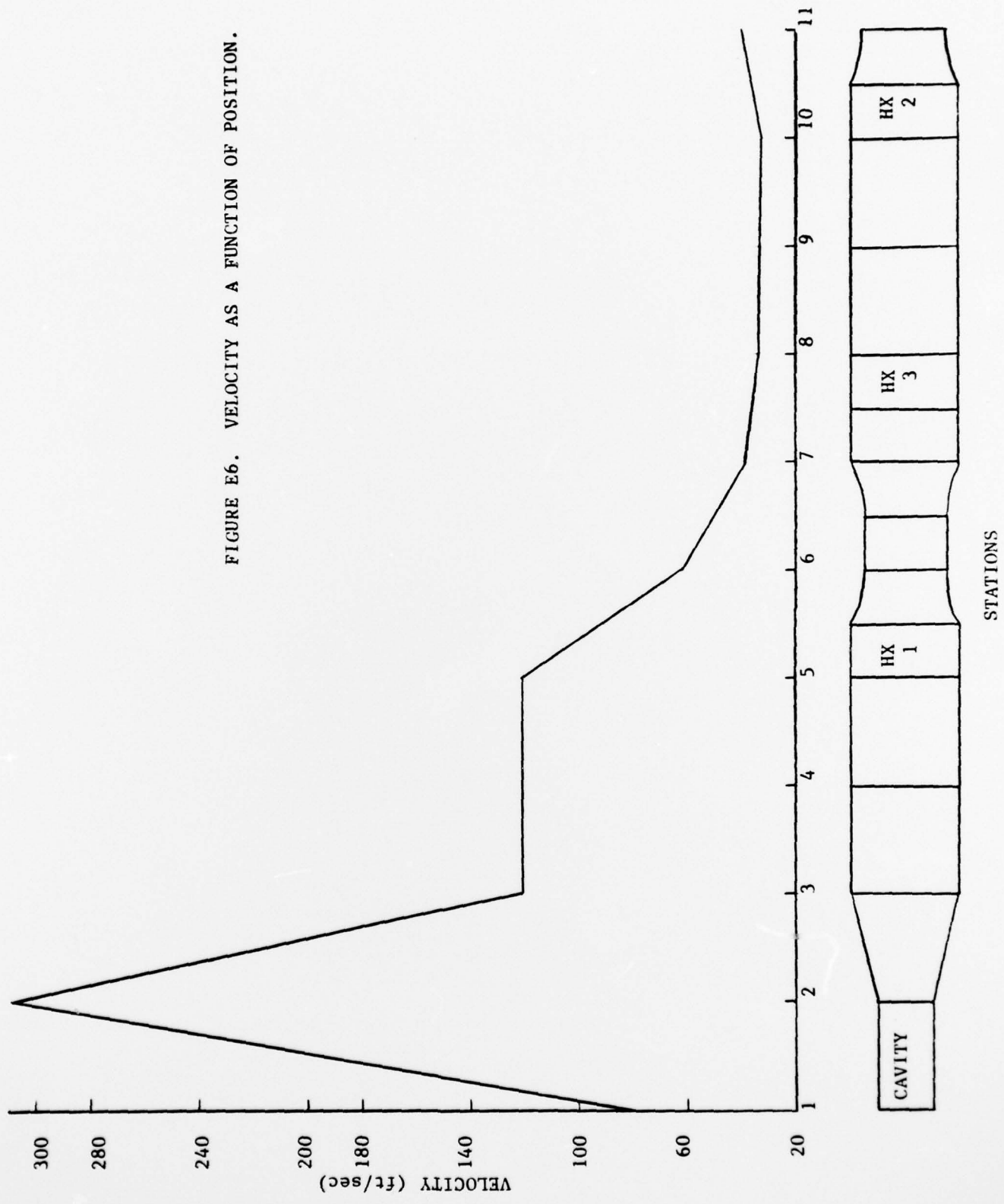


FIGURE E6. VELOCITY AS A FUNCTION OF POSITION.

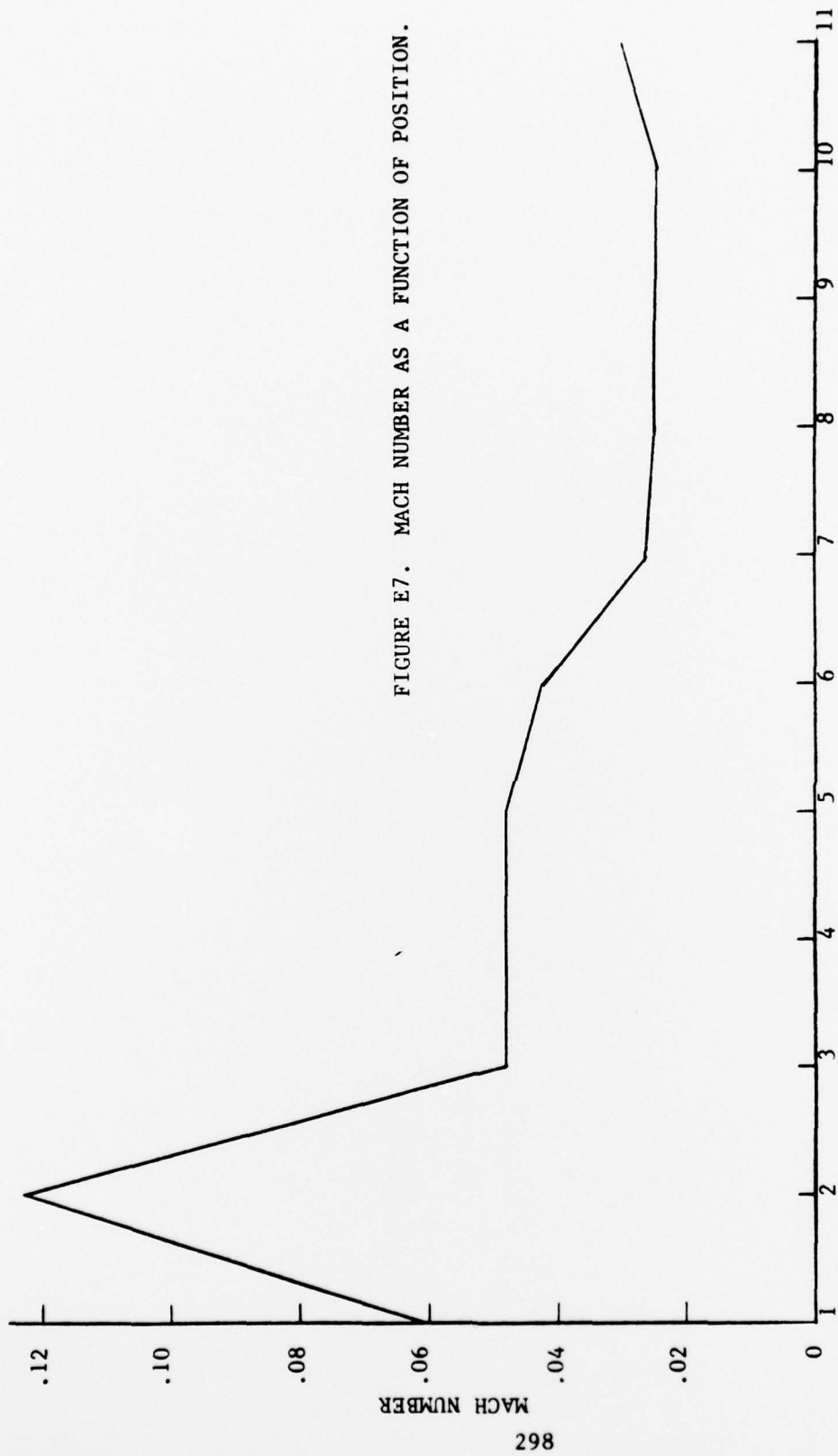
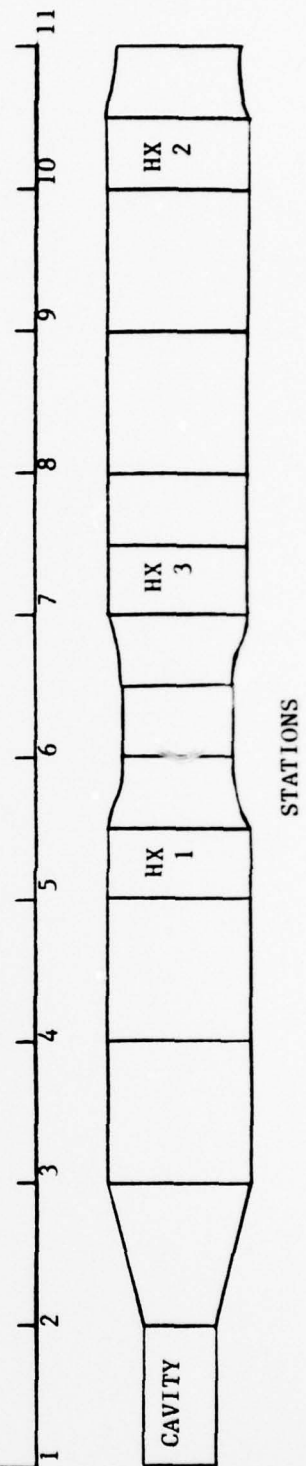


FIGURE E7. MACH NUMBER AS A FUNCTION OF POSITION.



DAAK40-77-C-0161  
The Univ. of AL in Huntsville

REPORTS DISTRIBUTION LIST

NUMBER OF COPIES

- |    |   |   |
|----|---|---|
| 1. | Defense Advanced Research Projects Agency<br>ATTN: Director, Laser Division<br>1400 Wilson Boulevard<br>Arlington, VA 22209                             | 1 |
| 2. | ODDR&E<br>ATTN: Assistant Director (Space & Advanced Systems)<br>The Pentagon<br>Washington, DC 20301   | 1 |
| 3. | National Aeronautics and Space Administration<br>Lewis Research Center<br>ATTN: Dr. John W. Dunning, Jr.<br>21000 Brookpark Road<br>Cleveland, OH 44135 | 1 |
| 4. | Defense Documentation Center<br>Cameron Station<br>Alexandria, VA 22314   | 2 |
| 5. | Department of the Army<br>DCSRDA<br>ATTN: DAMA-WSM-A (LTC Holmes)<br>Washington, DC 20310   | 1 |
| 6. | Commander<br>US Army Missile Research and Development Command<br>ATTN: DRDMI-HSE (Dr. Werkheiser)<br>Redstone Arsenal, AL 35809                         | 5 |
| 7. | Commander<br>US Army Missile Research and Development Command<br>ATTN: DRCPM-HEL<br>Redstone Arsenal, AL 35809  | 1 |
| 8. | Commander<br>US Army Mobility Equipment R&D Command<br>ATTN: AMXFB-EA (L. Amstutz)<br>Fort Belvoir, VA 22060  | 1 |

NUMBER OF COPIES

- |     |   |   |
|-----|---|---|
| 9.  | Commander<br>US Army Materiel Development and Readiness Command<br>ATTN: DRCRD-T (Dr. David Stefanye)<br>5001 Eisenhower Avenue<br>Alexandria, VA 22304 | 1 |
| 10. | Commander<br>US Army Electronics R&D Command<br>ATTN: DRSEL-CT-L (Dr. R. G. Buser)<br>Fort Monmouth, NJ 07703   | 1 |
| 11. | CPT James G. Wilson<br>Project Manager, High Energy Laser Project<br>US Naval Sea Systems Command<br>PMS 405<br>Washington, DC 20362                    | 1 |
| 12. | US Air Force Weapons Laboratory<br>ATTN: COL Donald L. Lambertson (AR)<br>Kirtland AFB, NM 87117  | 1 |
| 13. | US Air Force Aero Propulsion Laboratory<br>ATTN: MAJ George Uhlig (AFAPL/NA)<br>Wright Patterson AFB, OH 45433  | 1 |
| 14. | Dr. Walter Warren<br>Aerospace Corporation<br>Post Office Box 92957<br>Los Angeles, CA 90009  | 1 |
| 15. | Mr. A. Colin Stancliffe<br>Airesearch Manufacturing Company<br>2525 West 190th Street<br>Torrance, CA 90503   | 1 |
| 16. | Dr. Jack Daugherty<br>AVCO-Everett Research Laboratory<br>2385 Revere Beach Parkway<br>Everett, MA 02149  | 2 |
| 17. | Mr. Fred Tietzel (STOLAC)<br>Battelle Columbus Laboratories<br>505 King Avenue<br>Columbus, OH 43201  | 1 |



NUMBER OF COPIES

18.	Dr. Arthur N. Chester Hughes Research Laboratories 3011 Malibu Canyon Road Malibu, CA 90265	1
19.	Dr. Eugene Peressini (Bldg 6, MS/E-125) Hughes Aircraft Company Centinela & Teale Streets Culver City, CA 90230	1
20.	Lawrence Livermore Laboratory ATTN: Dr. John Emmett Post Office Box 808 Livermore, CA 94550	1
21.	Dr. Keith Boyer (MS 530) Los Alamos Scientific Laboratories Post Office Box 1663 Las Alamos, NM 87544	1
22.	Mr. Peter H. Rose Mathematical Sciences Northwest, Inc. 4545 15th Avenue, NE Seattle, WA 98105	1
23.	Massachusetts Institute of Technology Lincoln Laboratories ATTN: Dr. Rediker Post Office Box 73 Lexington, MA 02173	1
24.	Dr. Gerard Hasserjian Northrop Corporation 3401 West Broadway Hawthorne, CA 90250	1
25.	Mr. Marc T. Constantine Rocketdyne Division Rockwell International Corporation 6637 Canoga Avenue Canoga Park, CA 91304	1

DAAK40-77-C-0161

The Univ. of AL in Huntsville

	<u>NUMBER OF COPIES</u>
26. Mr. Harvey Ford Science Applications, Inc. 6666 Powers Ferry Road, Suite 202 Atlanta, GA 30339	1
27. Mr. Alan F. Klein Systems, Science and Software Post Office Box 1620 LaJolla, CA 92037	1
28. Mr. G. H. McLafferty United Aircraft Research Laboratory 400 Main Street East Hartford, CT 06108	1
29. Mr. W. F. List Westinghouse Electric Corporation Defense and Space Center Friendship International Airport - Box 746 Baltimore, MD 21203	1